

Ferroelectrics in the age of Hyper-scaling

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IEEE EDS/SSCS Bangladesh Chapter
Dept of EEE, BUET
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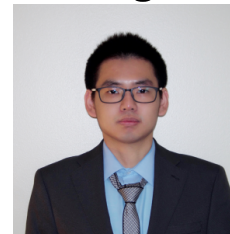


arm

NORTHROP GRUMMAN

And many more

Zheng W.



Sarah L.



Nujhat T.



Anthony G.



Moments Ago
White House

SOON: White House
Press Briefing

BREAKING NEWS

TRUMP MEETS WITH INTEL CEO

CNN

10:08 AM PT

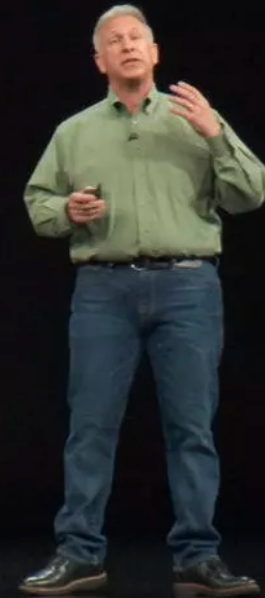
WOLF

February 2017

<https://www.cnn.com/videos/politics/2017/02/08/intel-ceo-meets-with-president-donald-trump-new-product-bts.cnn>

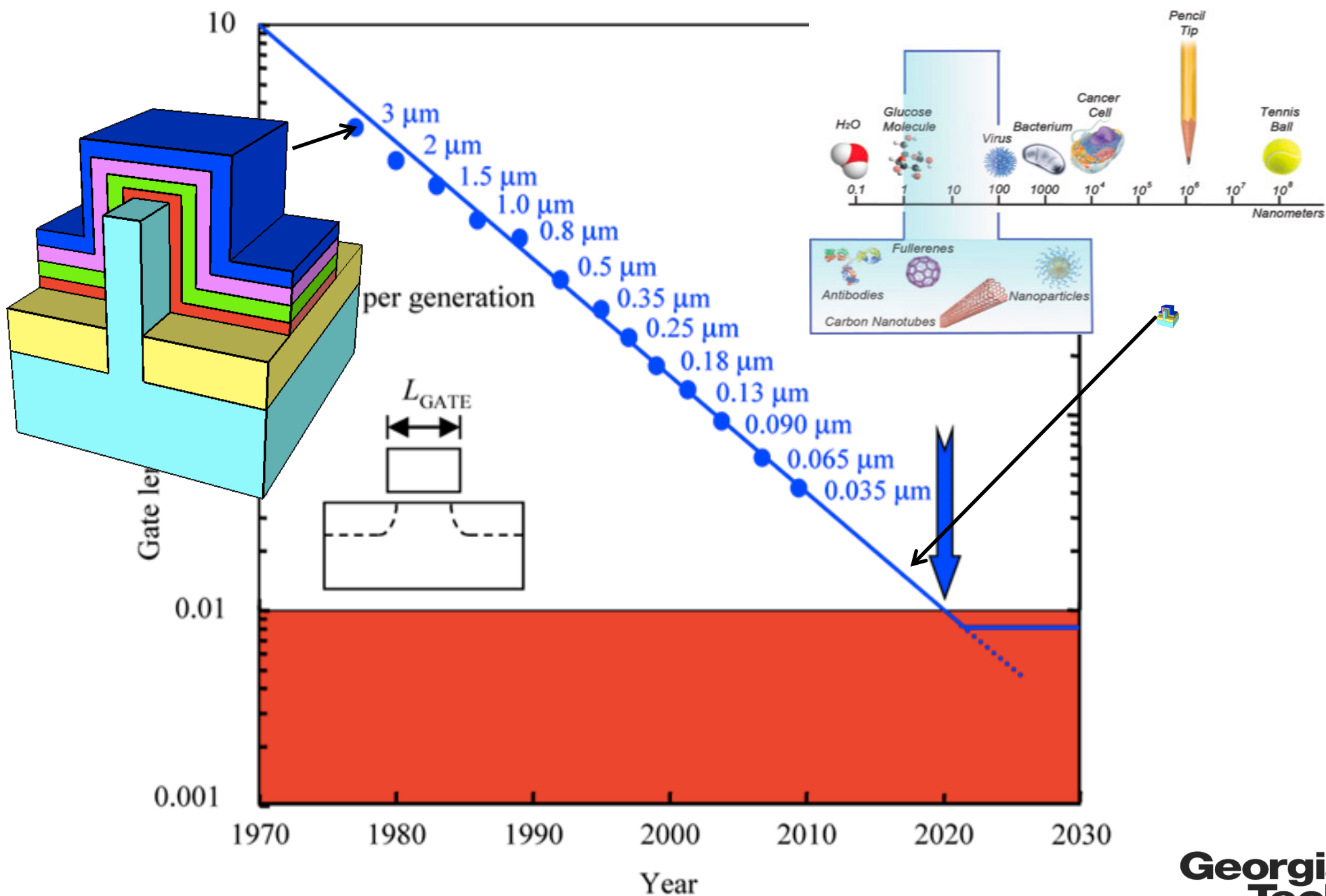
6.9 billion

Transistors

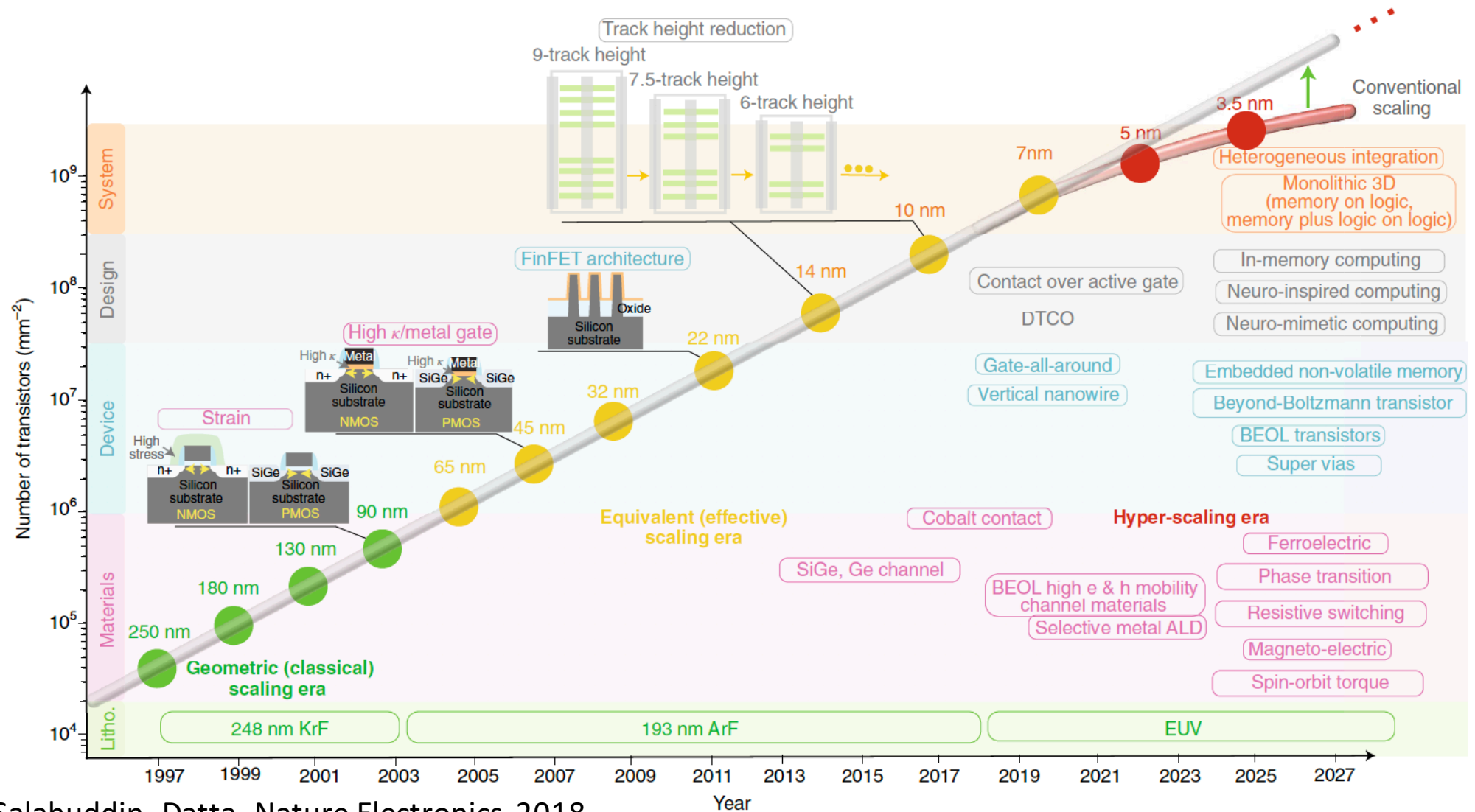


Late 2018

Moore's Law



End of Dimensional Scaling!



Salahuddin, Datta. Nature Electronics 2018

Is this the end of the Semiconductor Industry?

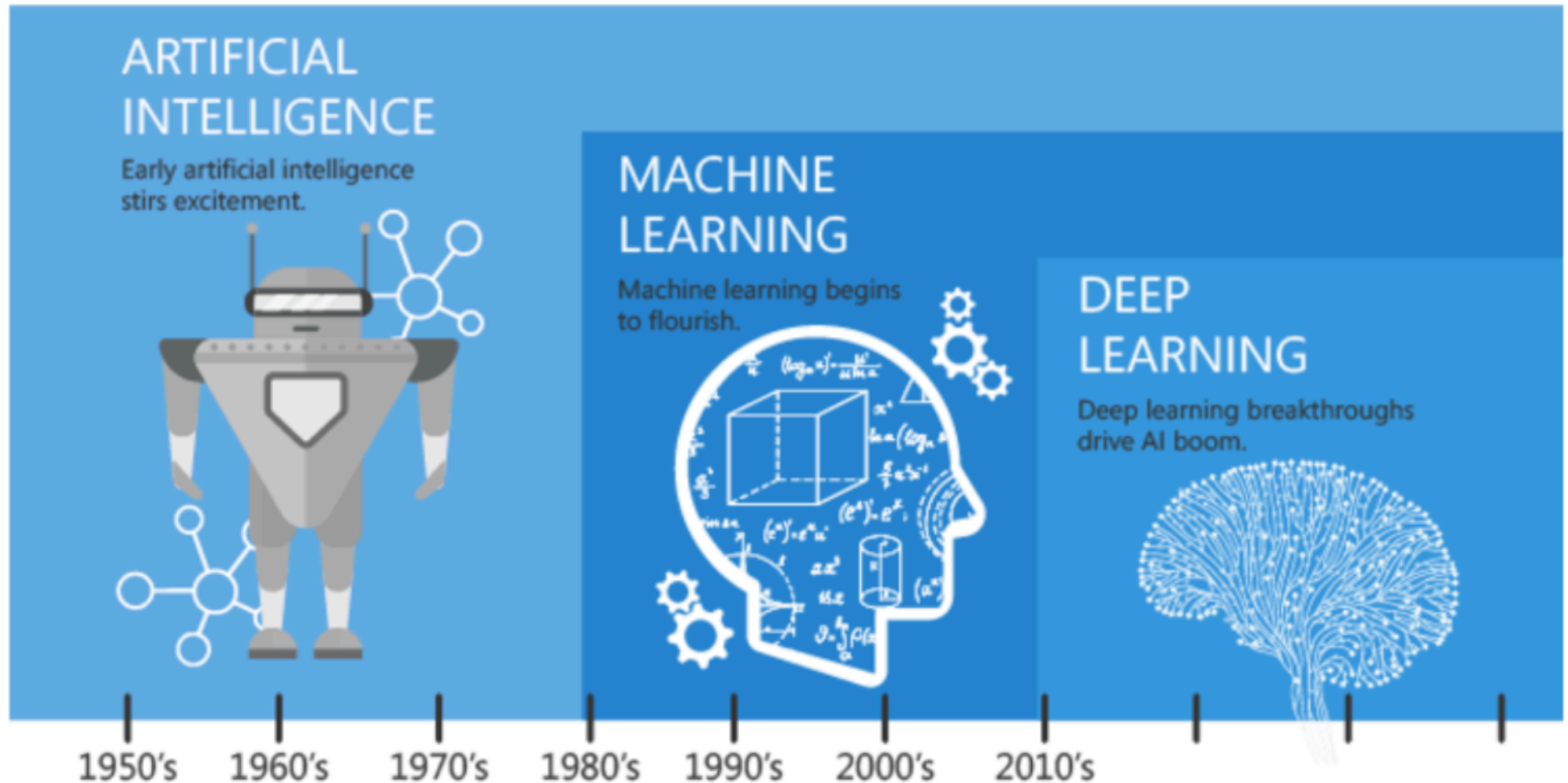
The Fourth Industrial Revolution!



Artificial Intelligence
Machine Learning
Autonomous agents and swarms

Augmented reality
Cyber physical systems
1 Trillion IoT devices?

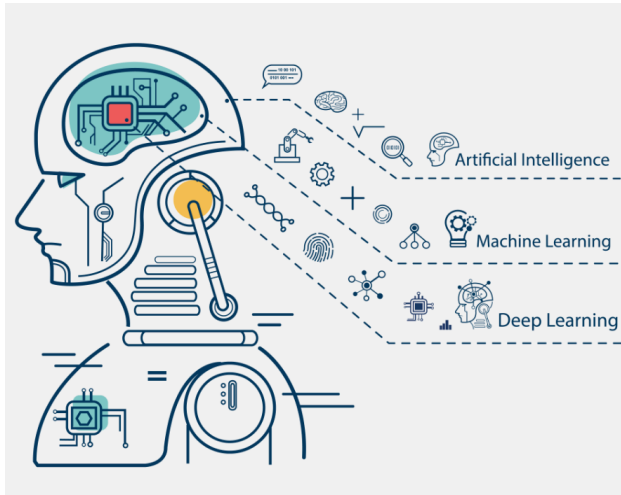
Artificial Intelligence & Machine Learning!



What led to this boom?

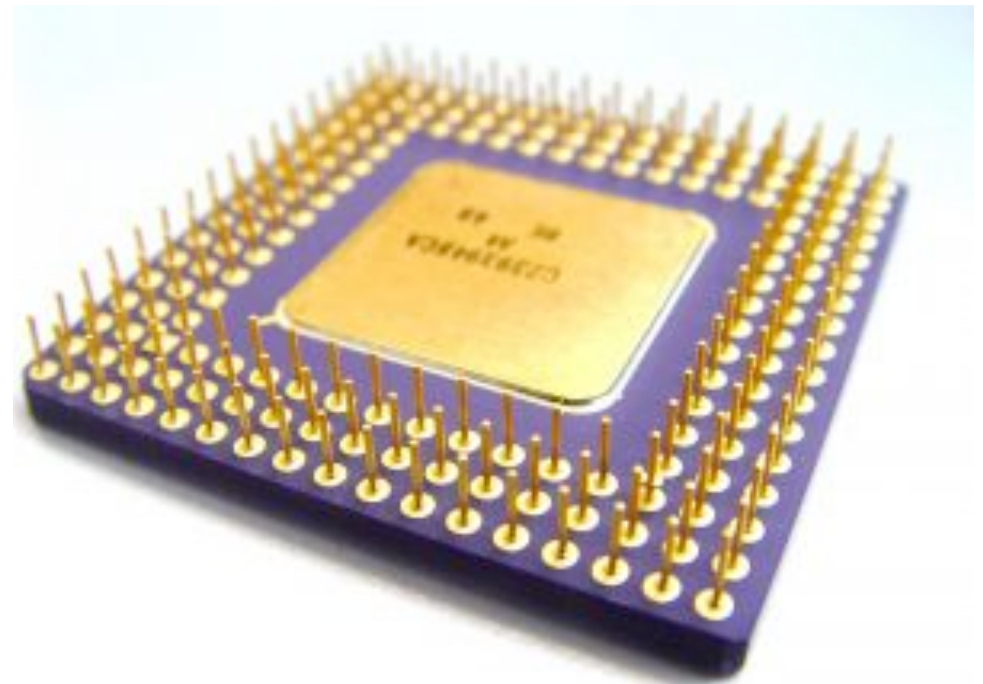
By 2010, CMOS became powerful enough that machine learning techniques especially deep neural networks (DNNs) could be deployed at relevant scales

Can we achieve these capabilities at scale?

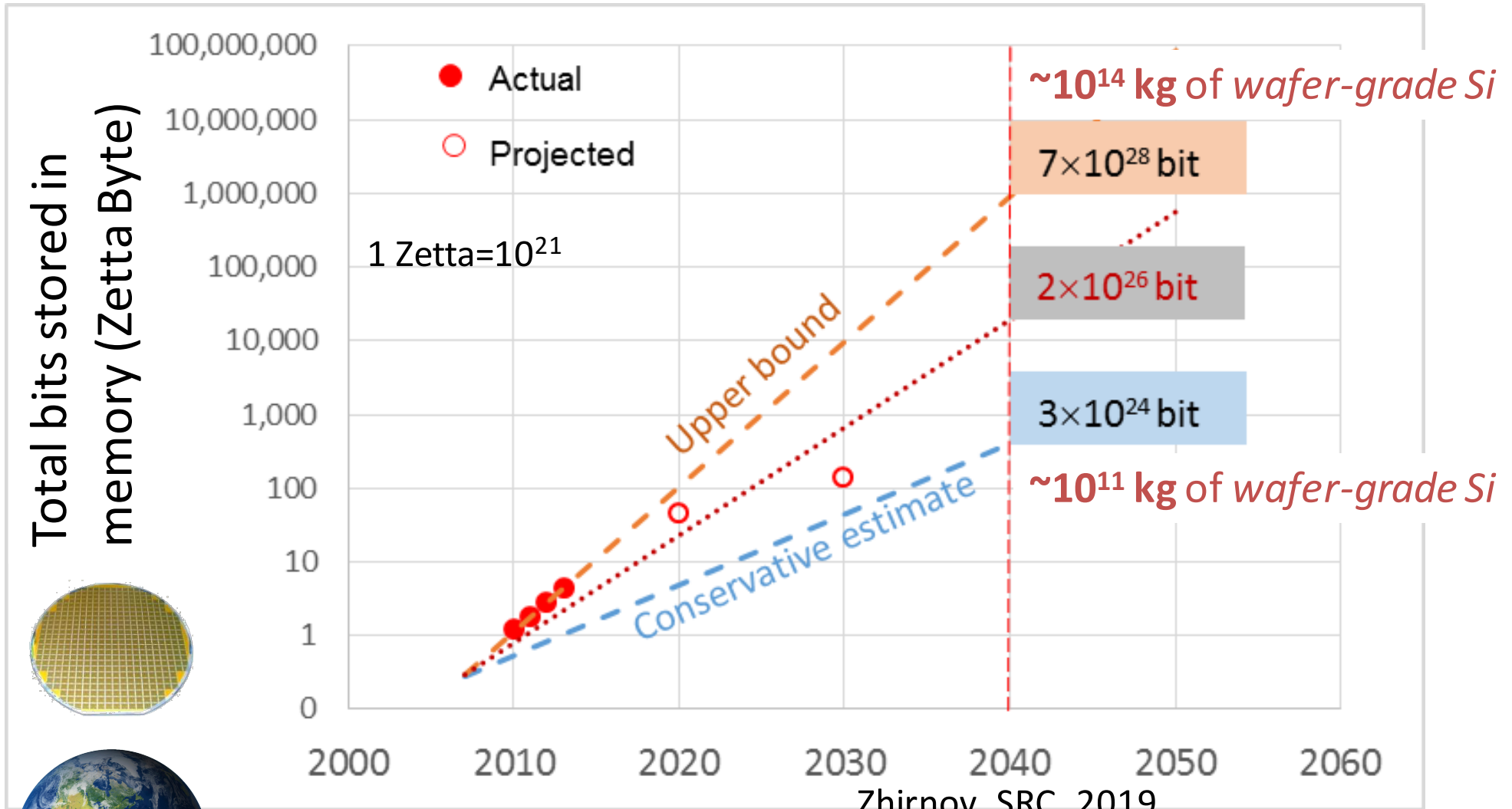


Is software enough?

??



How much Silicon do we need to sustain?



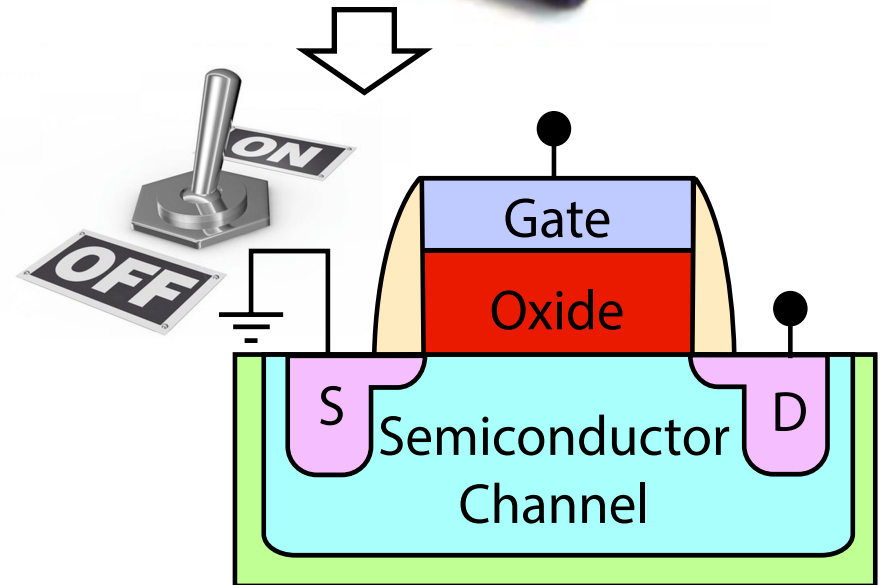
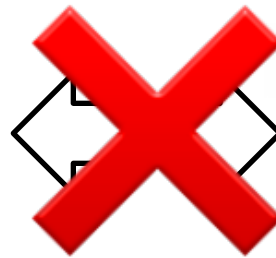
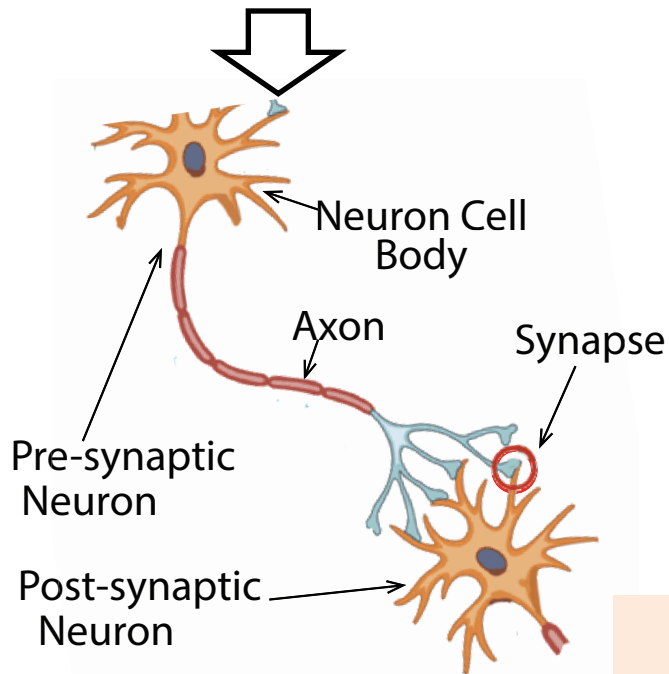
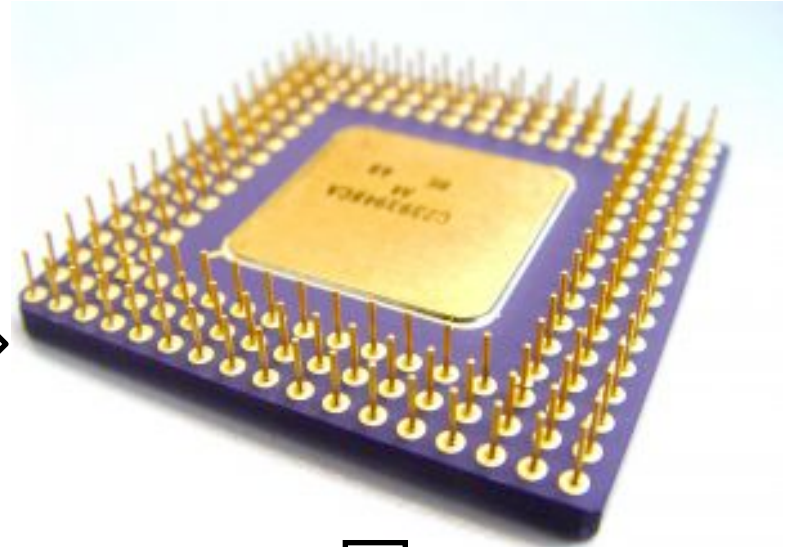
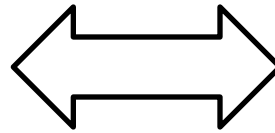
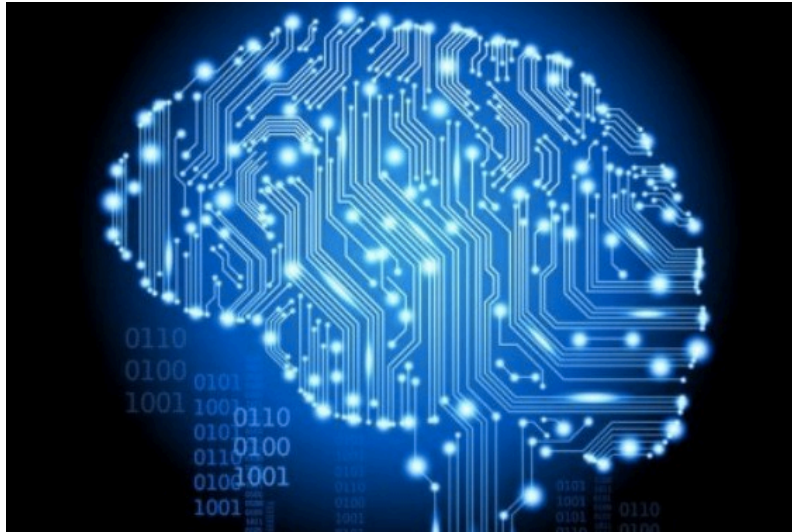
Zhirnov, SRC, 2019

Hilbert et al. *Science* 332 (2011) 60-65

Total Silicon needed in 2040 at least 10^{11} kg

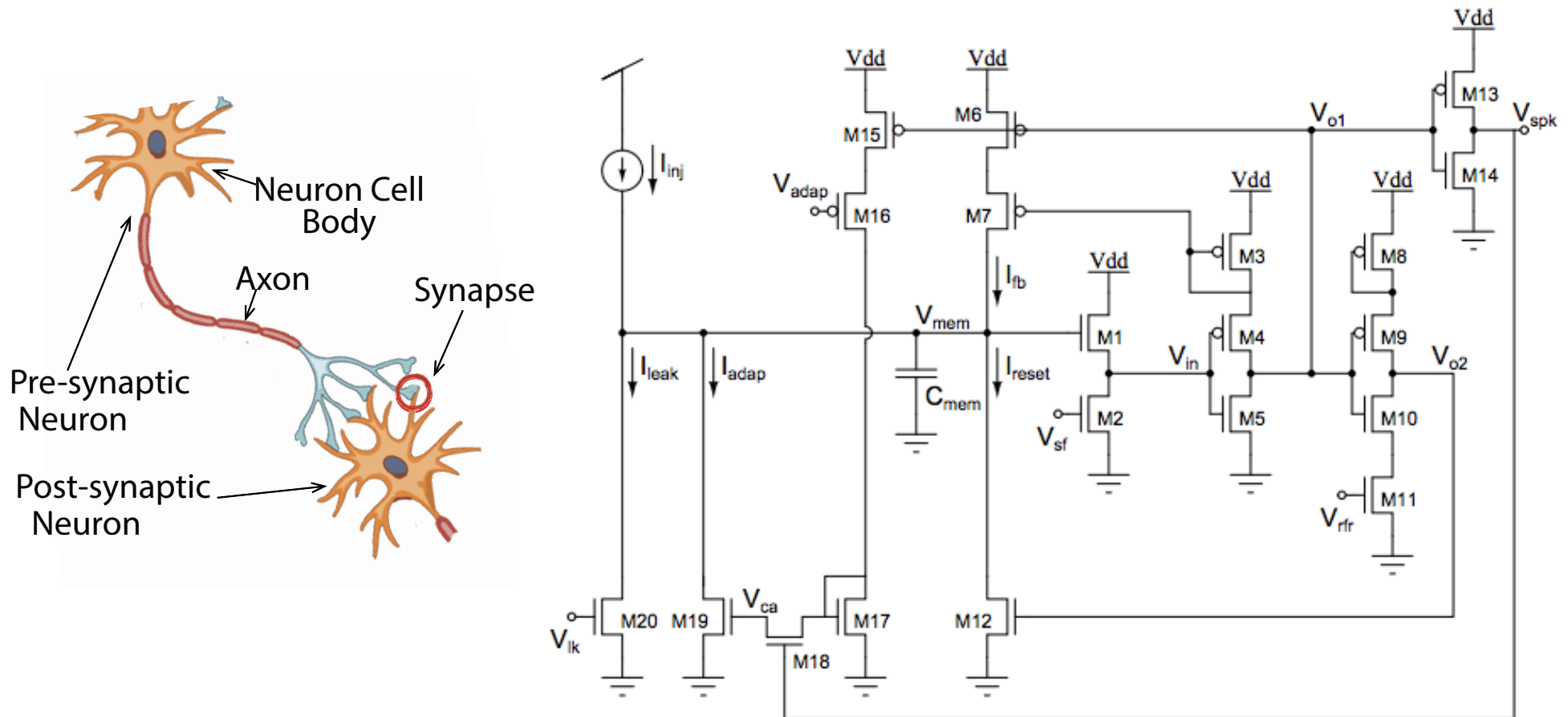
Projected annual global supply of Silicon wafers: 10^7 – 10^8 kg in 2040

Brain vs. Traditional Computers



CMOS Transistors are not
neuron-synapse analogues!

For example: CMOS Neurons



CMOS Transistors are not efficient when it comes to performing AI specific/neuromorphic tasks!

Indiveri et al. ISCAS 2003

Semiconductor Industry and Computing

Article
January 2019

Artificial-intelligence hardware: New opportunities for semiconductor companies

By [Gaurav Batra](#), [Zach Jacobson](#), [Siddarth Madhav](#), [Andrea Queirolo](#), and [Nick Santhanam](#)

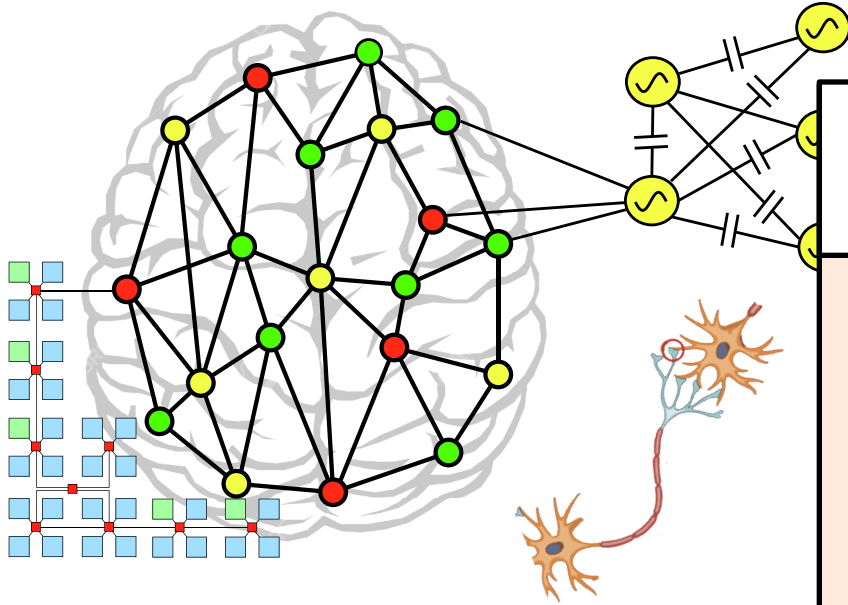
“AI could allow semiconductor companies to capture 40 to 50 percent of total value from the technology stack, representing the best opportunity they’ve had in decades.”

Historically the fraction has been 10-20% for the semiconductor industry!

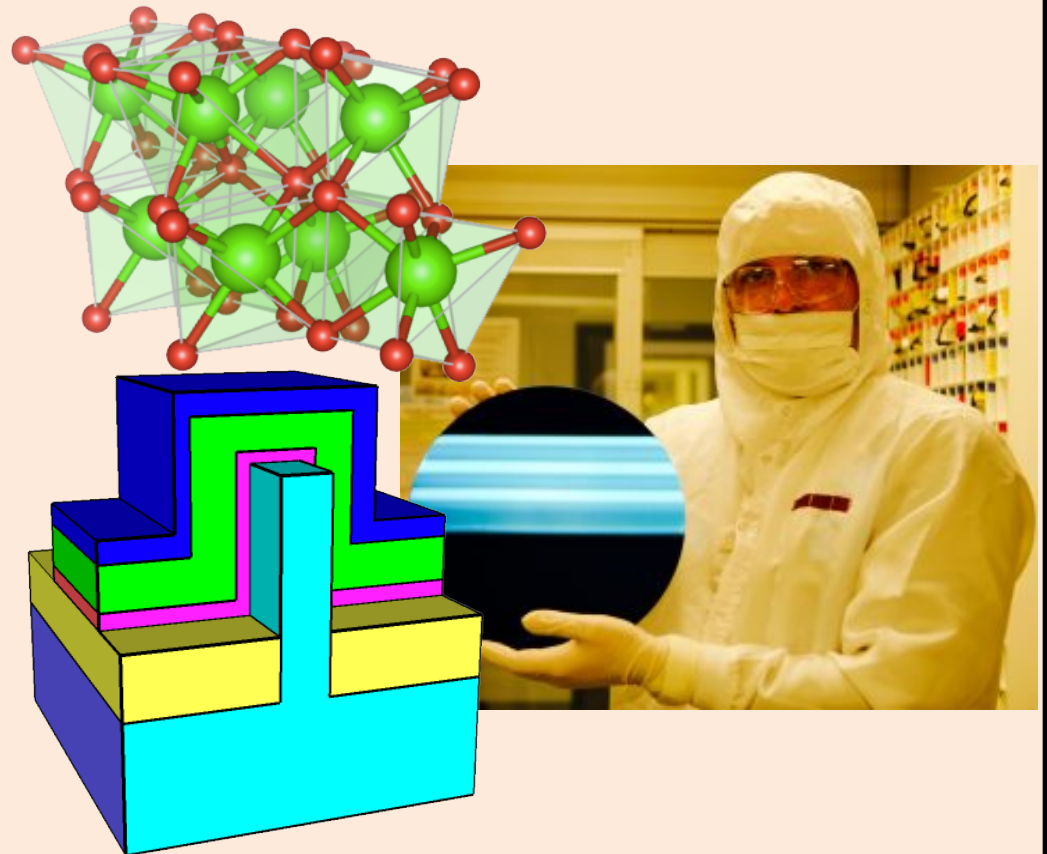
<https://www.mckinsey.com/industries/semiconductors/our-insights/artificial-intelligence-hardware-new-opportunities-for-semiconductor-companies>.

What do we do?

Advanced Computing Systems

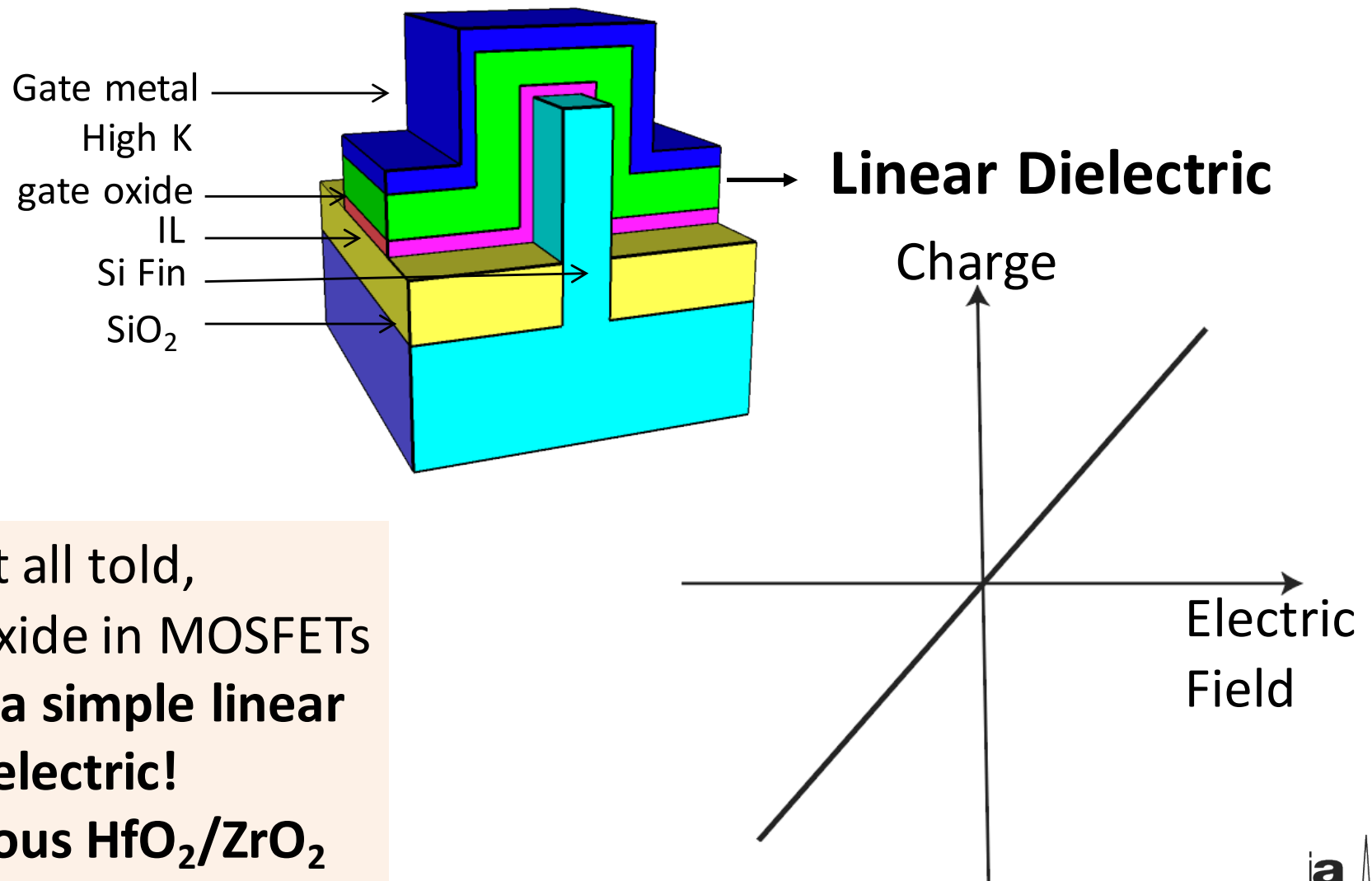


Advanced Devices and Materials With New Physics



The workhouse: The Transistor

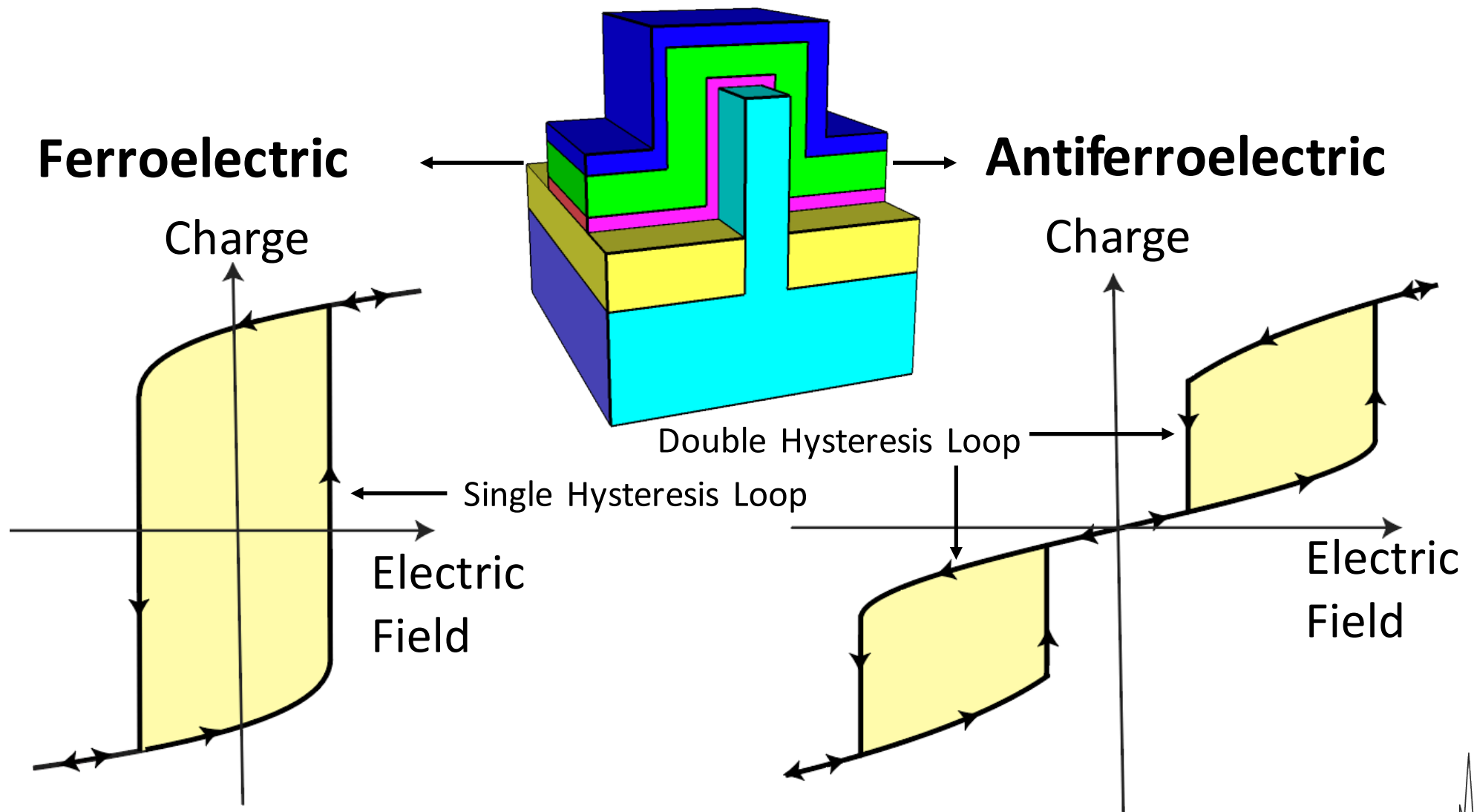
Engineering the MOSFET structure (**strain, HKMG, FinFET, NW etc.**) has been crucial in augmenting the performance.



But all told,
The gate oxide in MOSFETs
has been a **simple linear
dielectric!**
Amorphous HfO₂/ZrO₂

Ferroelectricity and Antiferroelectricity

Functional augmentation of Transistor by replacing the high-K with a FE/AFE Gate oxide (non-linear dielectric)!



Ferroelectricity and Antiferroelectricity

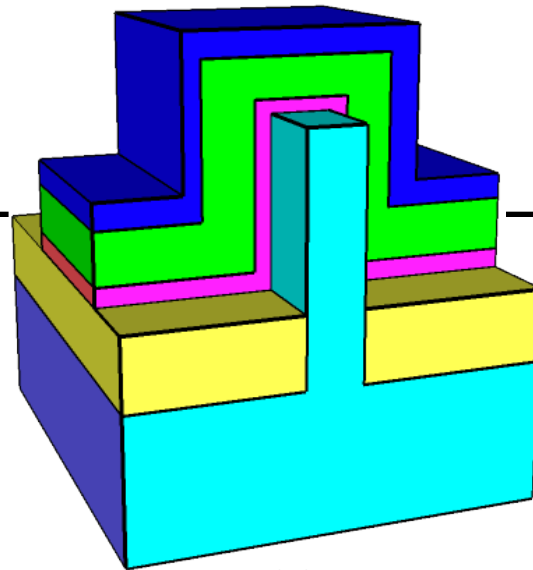
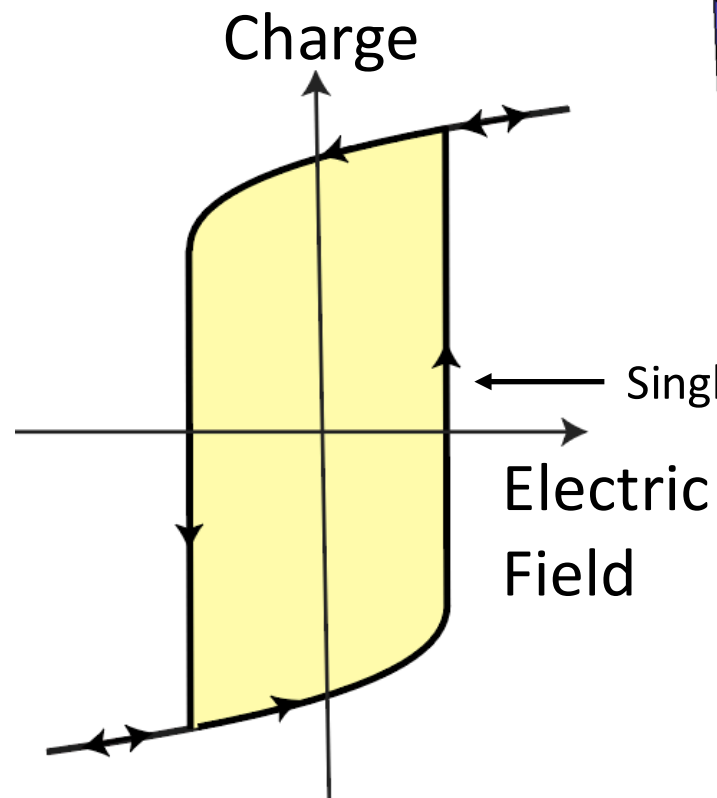
Why is a drop-in replacement possible? Standard high-K oxides: HfO_2 and ZrO_2 and their alloyed variants can become FE and AFE.

HfO_2 and its alloyed variants

Boscke et al. IEDM 2011

Muller et al. Nano Lett. 2012

Ferroelectric

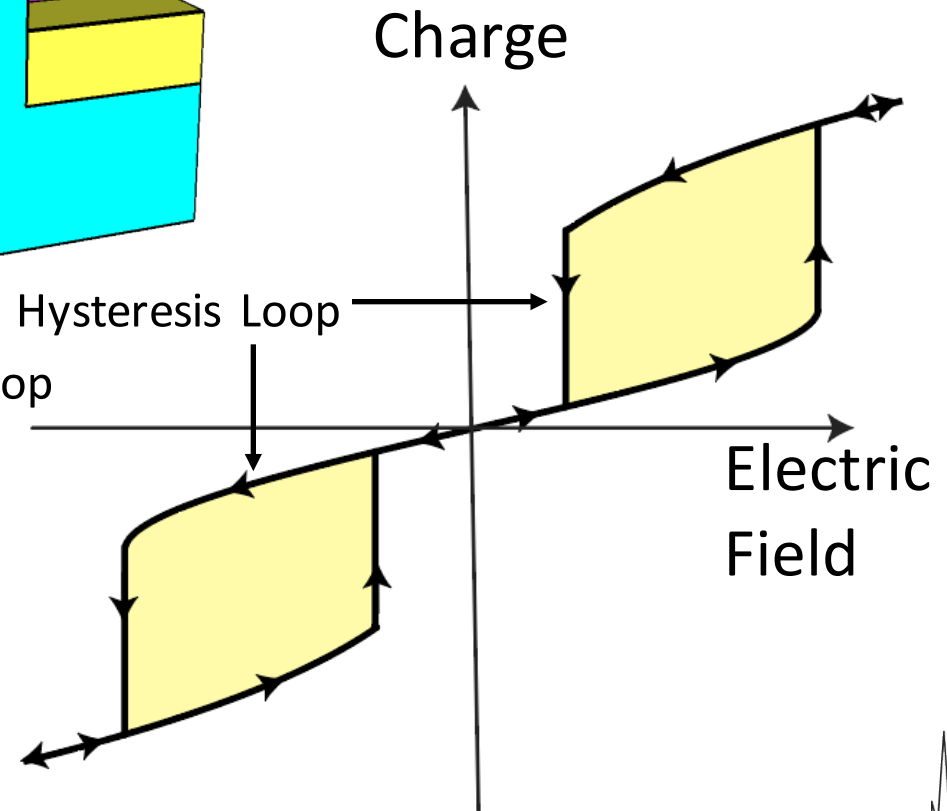


ZrO_2 and its alloyed variants

Muller et al. Nano Lett. 2012

Wang et al. APL 2018

Antiferroelectric



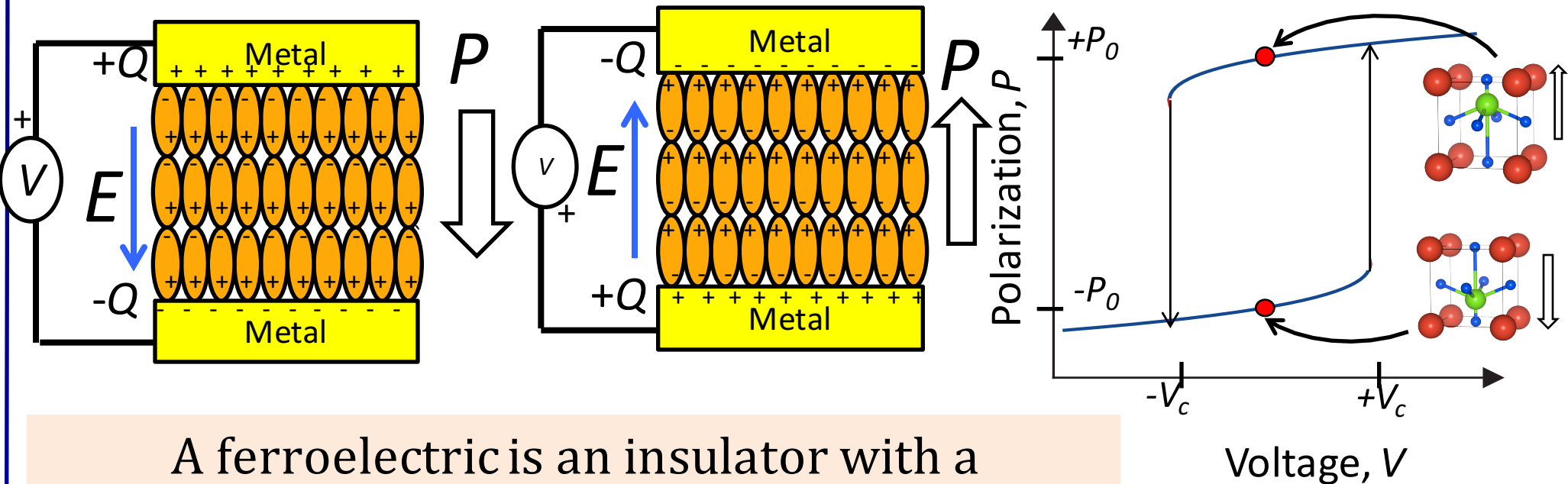
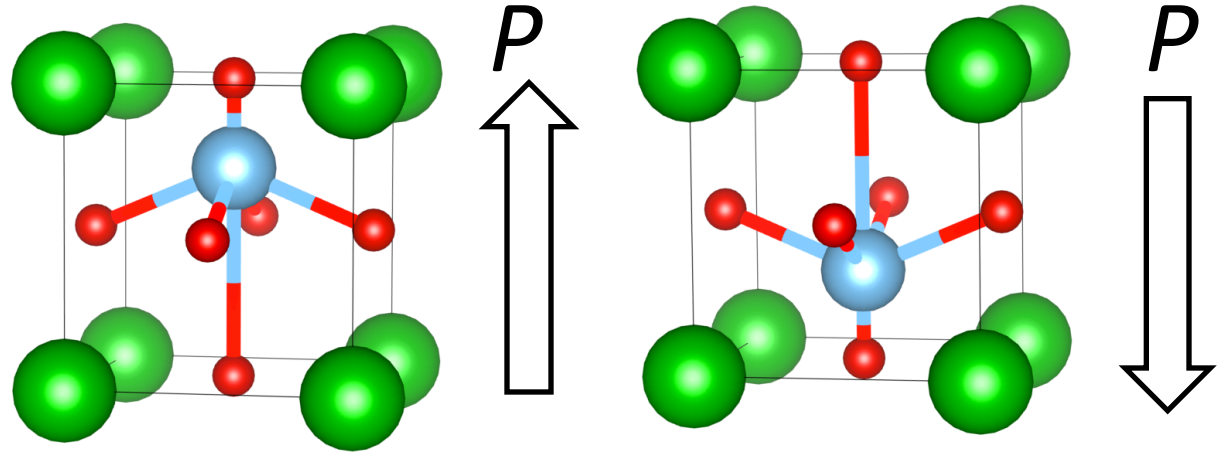
Double Hysteresis Loop

Single Hysteresis Loop

Ferroelectric Oxides

Classical Ferroelectric
 PbTiO_3 , BaTiO_3 etc.

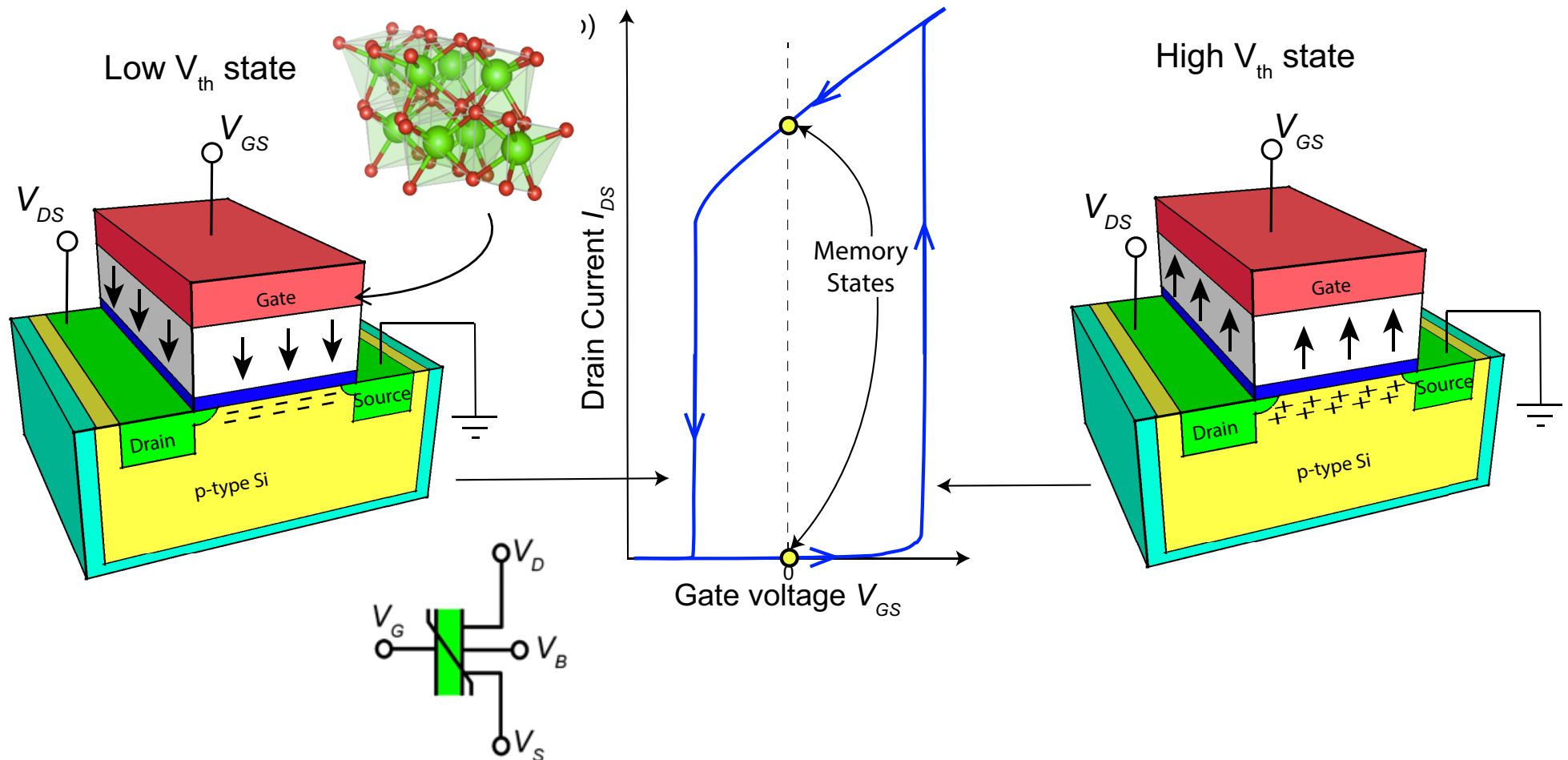
Emerging CMOS
compatible Ferroelectrics:
Doped HfO_2



A ferroelectric is an insulator with a spontaneous polarization, which can be switched by an above coercive voltage .

Ferroelectric Transistors

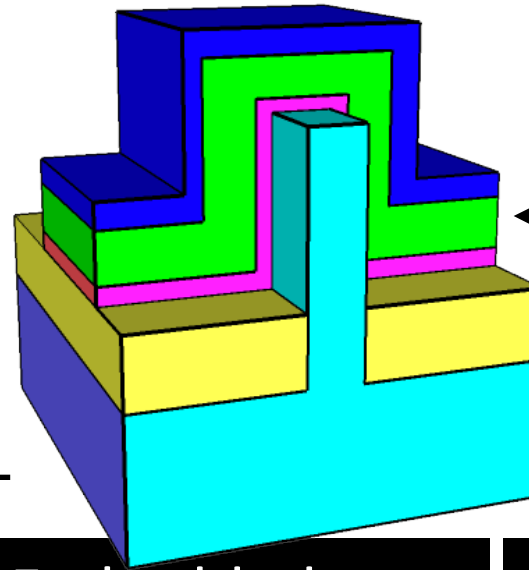
Ferroelectric Transistors (FEFET): Gate oxide stack includes a FE oxide



A ferroelectric transistor is a **hysteretic** device.

Ferroelectricity and Antiferroelectricity

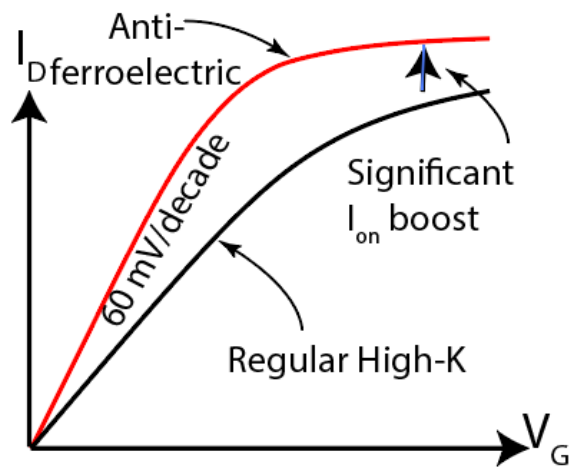
In similar device structures, FE/AFE-FETs can lead to functional diversification.



A Ferroelectric or Antiferroelectric Oxide

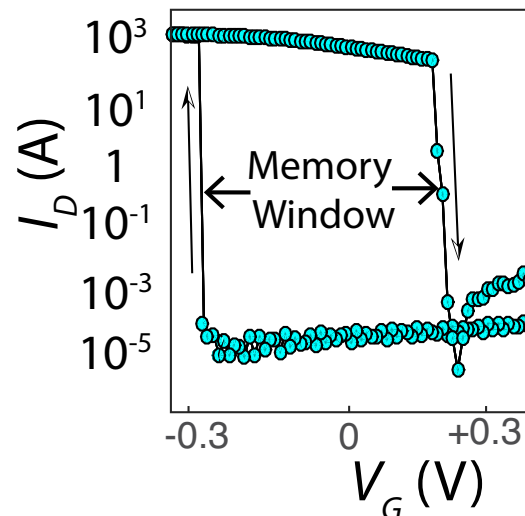
Sub-Boltzmann Logic Transistor

Negative Capacitance FET



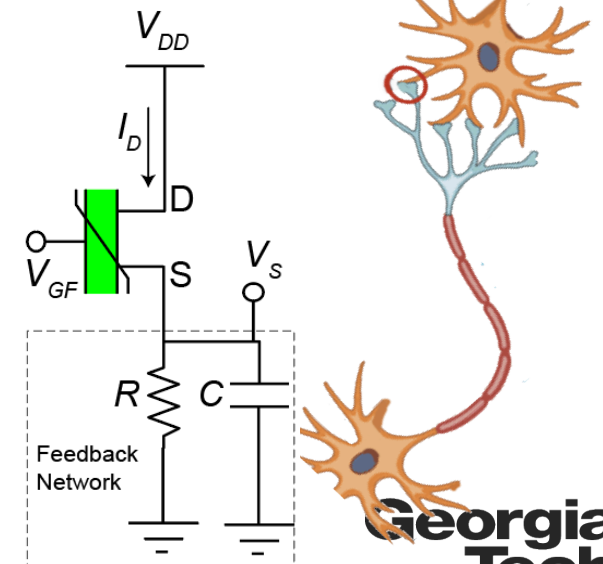
Embedded Memory

Non-volatile memory FET



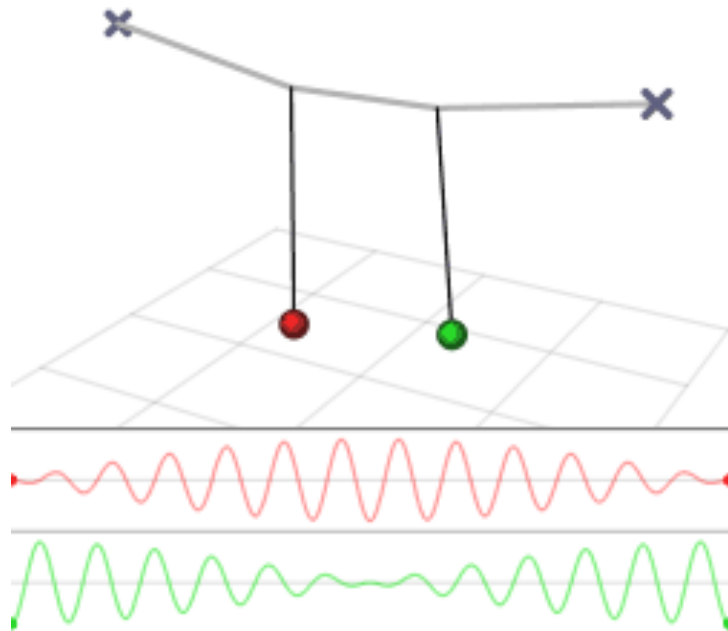
Non-von Neumann/ Neuromorphic

Neurons/Synapses



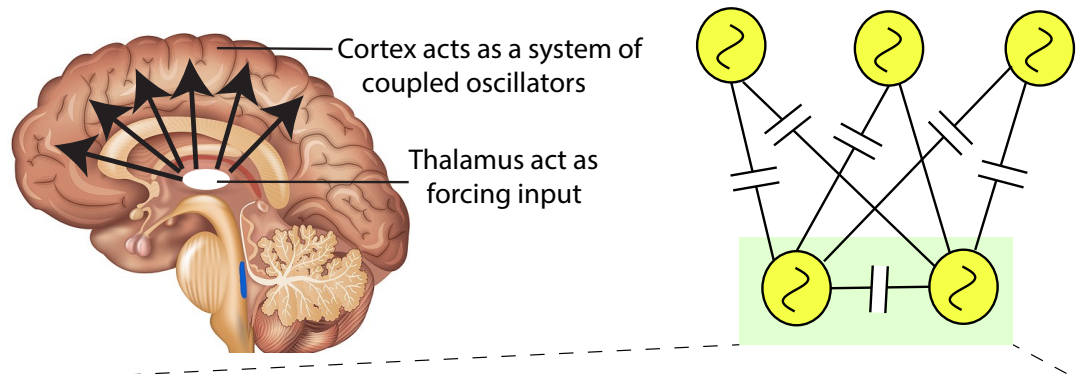
Example 1: Coupled Oscillatory Systems

A Coupled Oscillator System

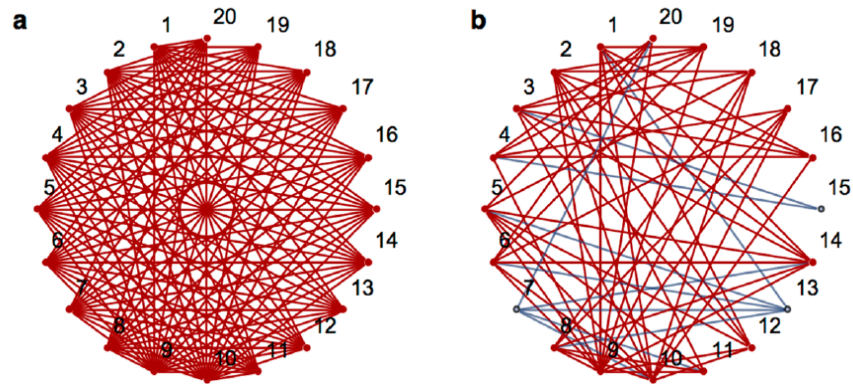


https://upload.wikimedia.org/wikipedia/commons/4/43/Coupled_oscillators.gif

A Ferroelectric Oscillator System



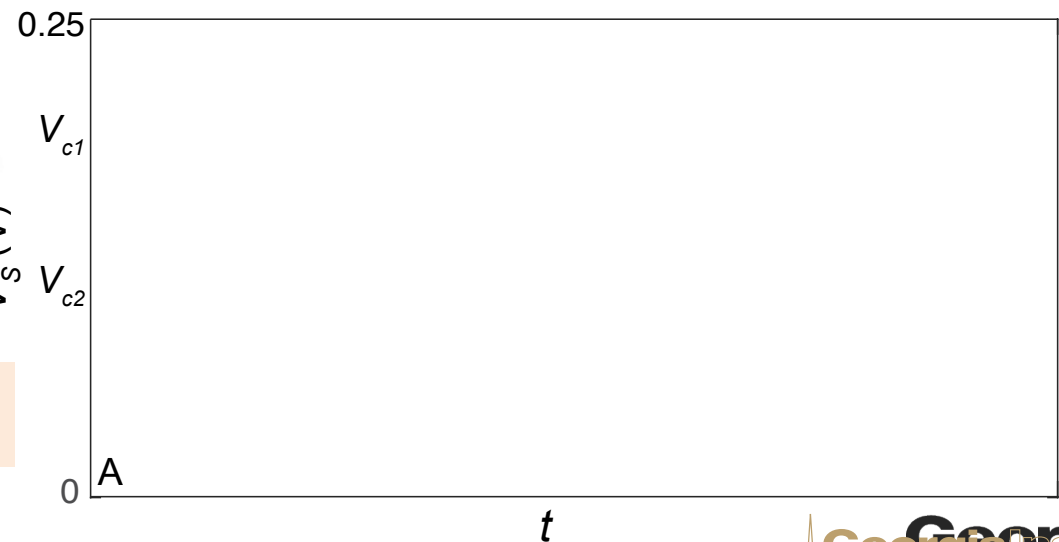
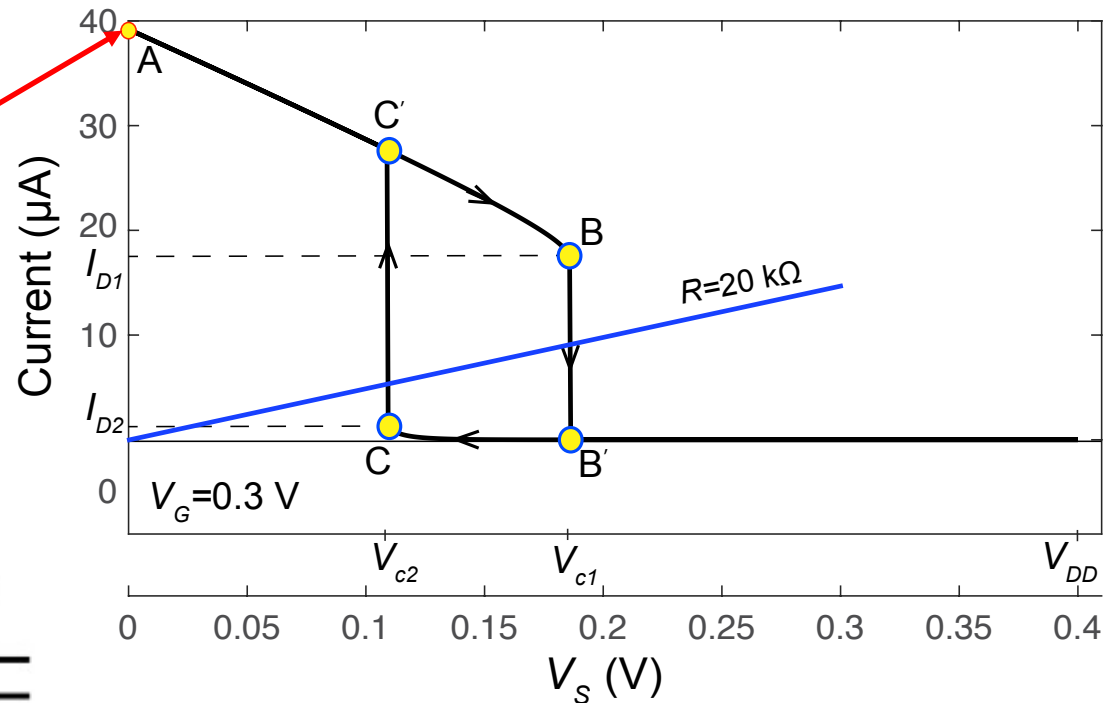
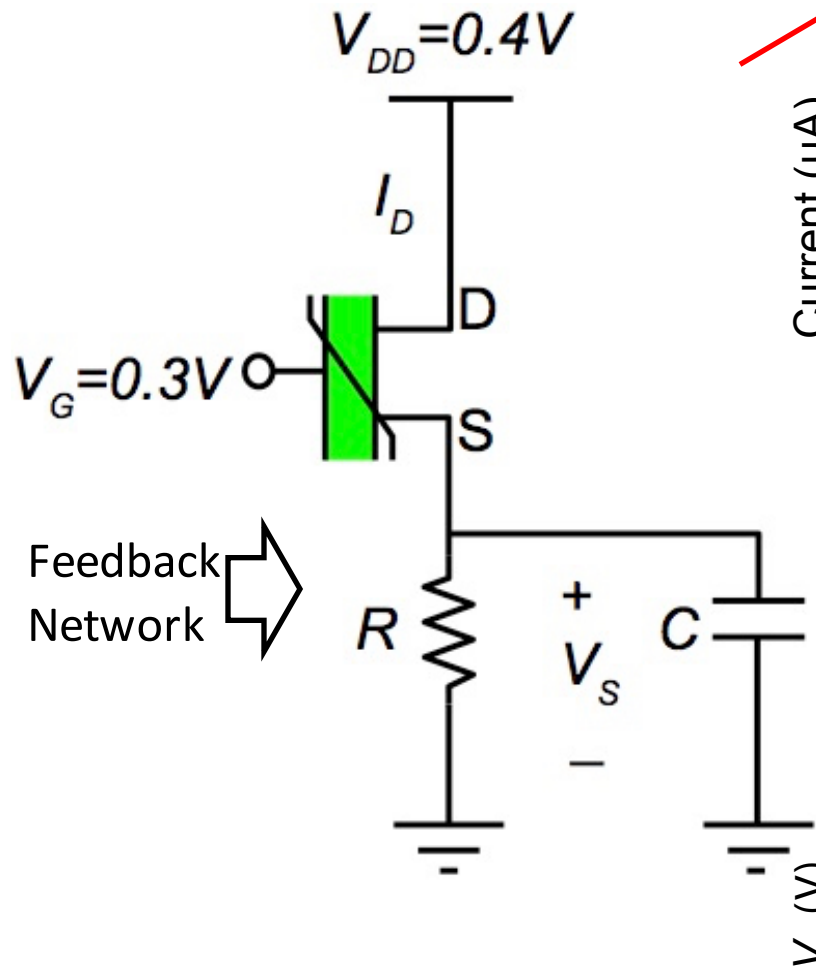
Computationally Hard Problems



Synchronization dynamics in coupled oscillatory system can be utilized to solve computationally hard problems!

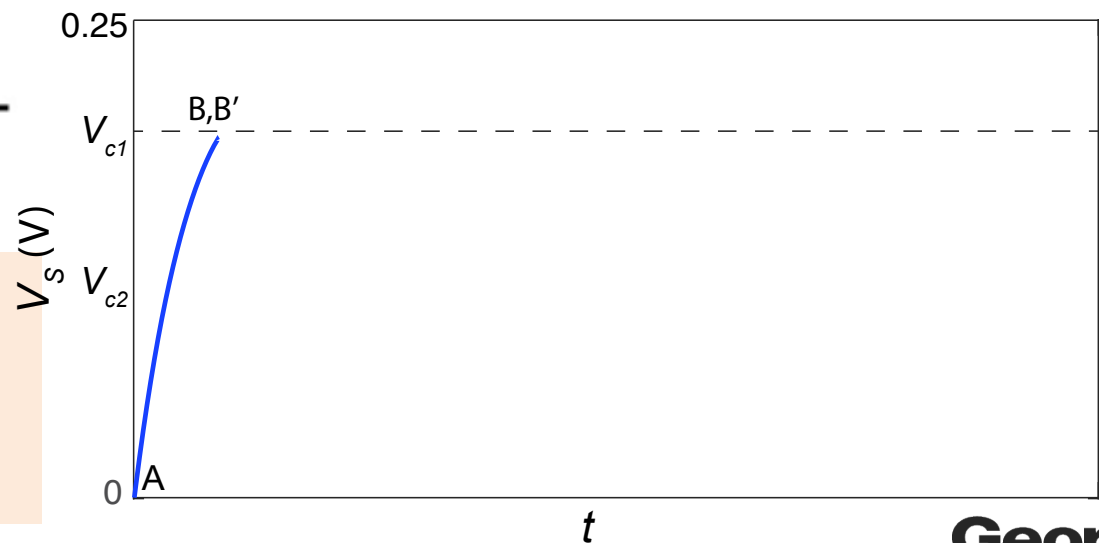
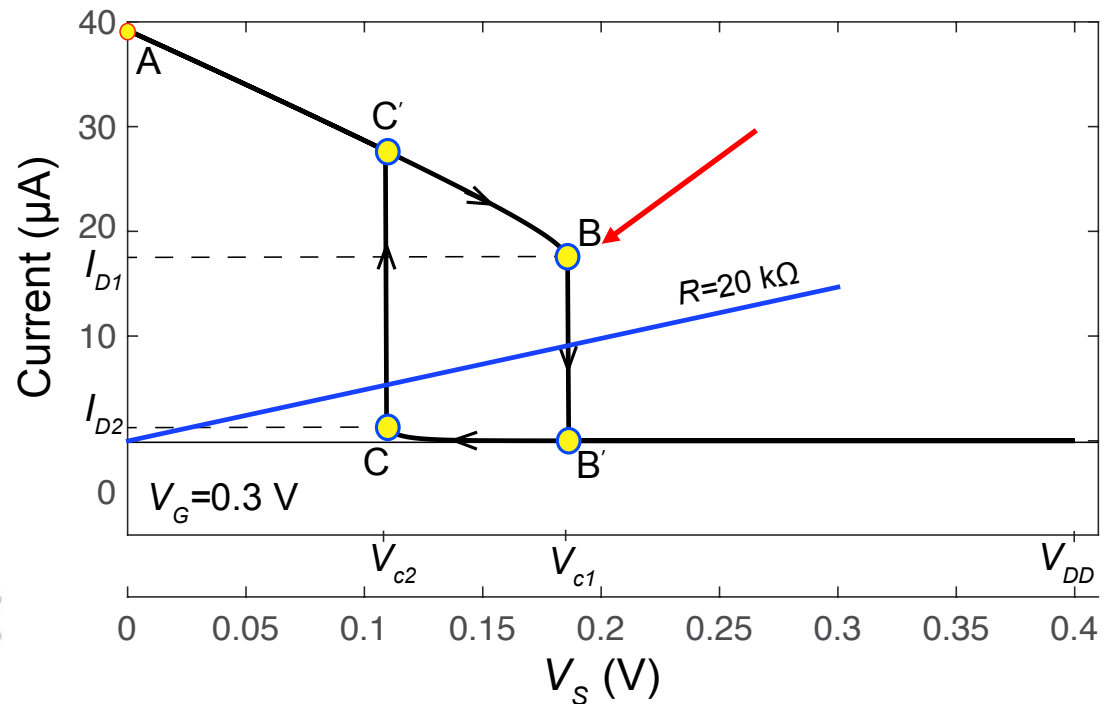
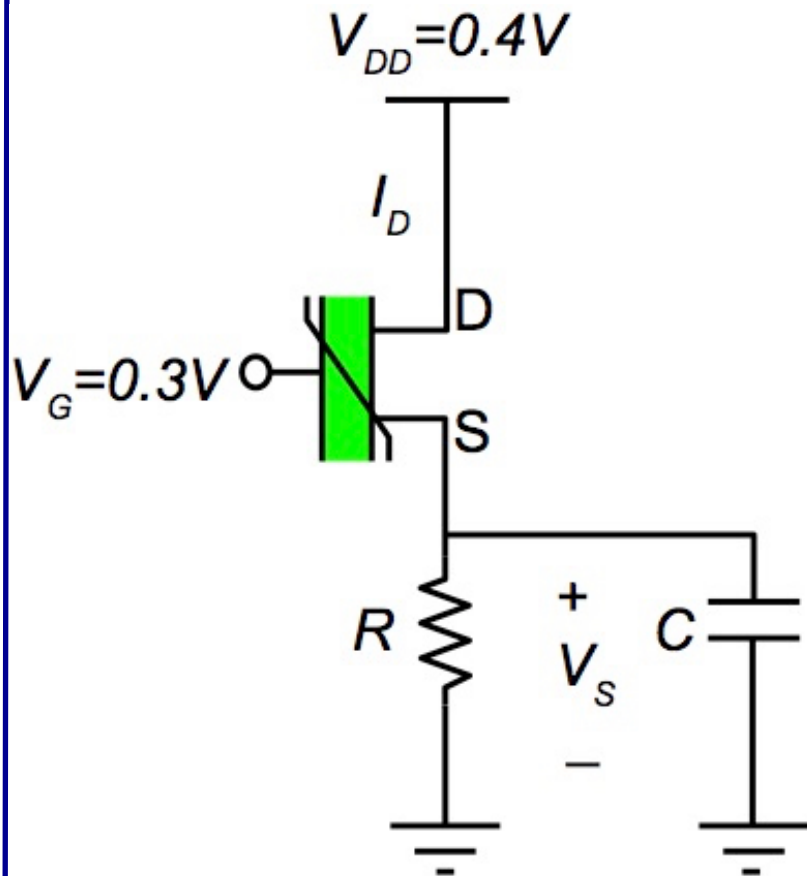
Shukla et al. Sci. Rep. 2014
Hoppensteadt et al. PRL 1998

Dynamics of Ferroelectric Oscillator



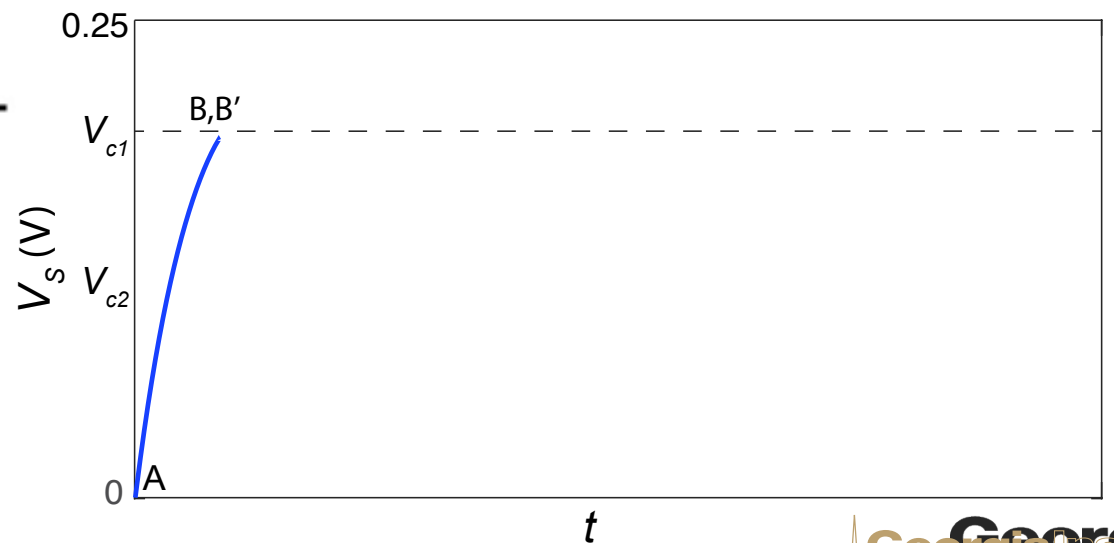
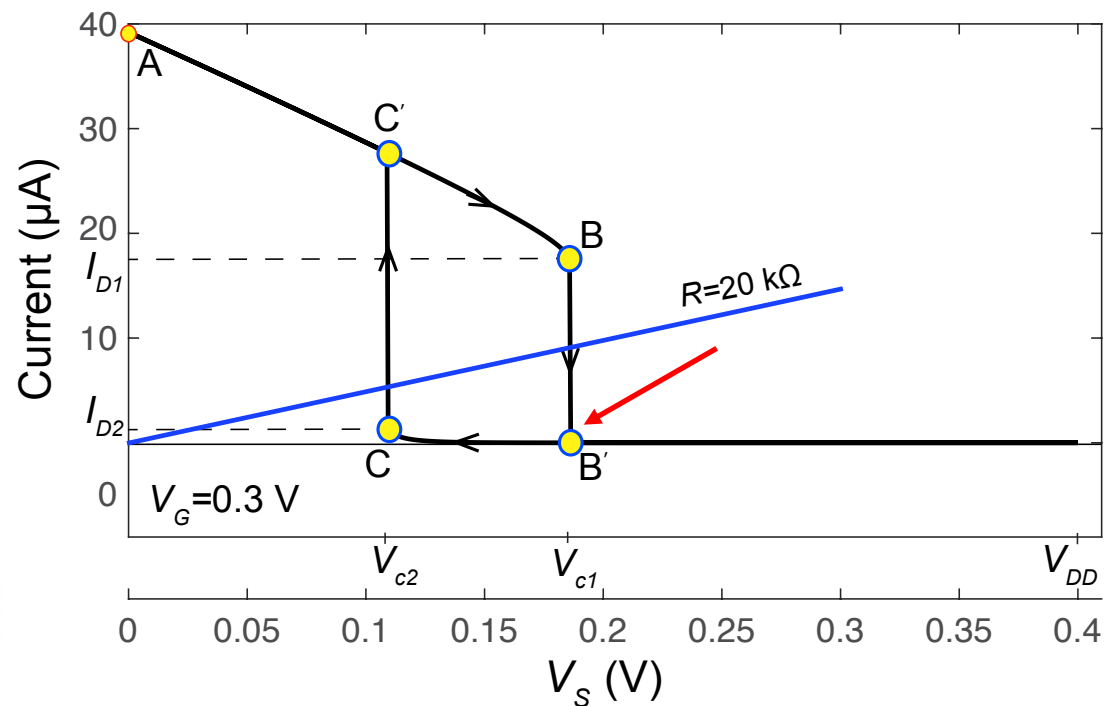
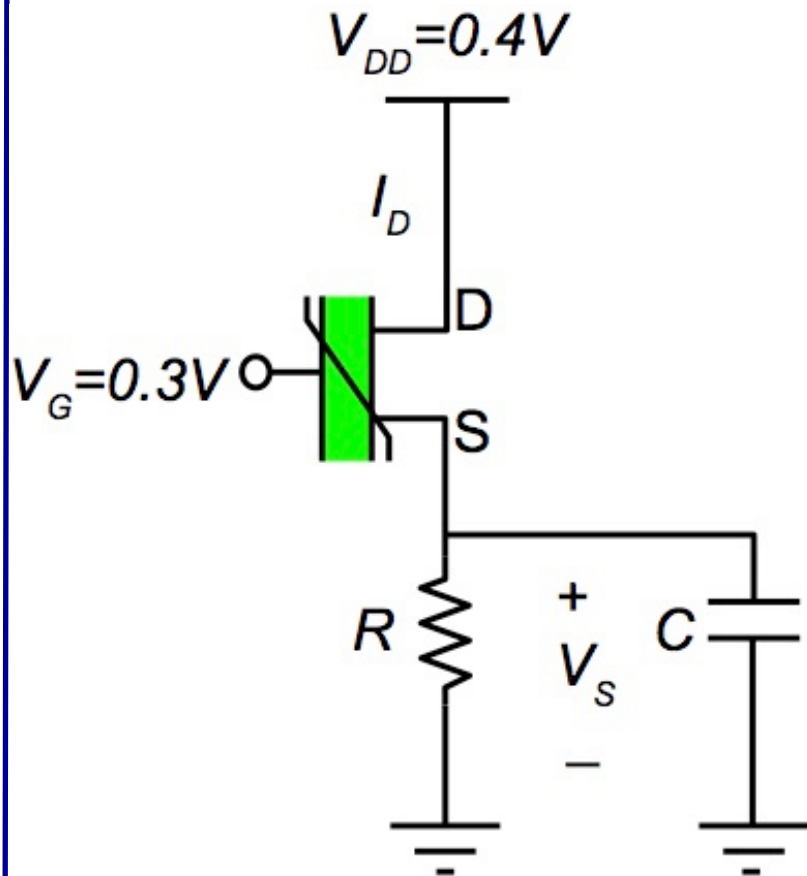
FEFET is at point A initially

Dynamics of Ferroelectric Oscillator



No stable states in the abrupt transition region between B and B'

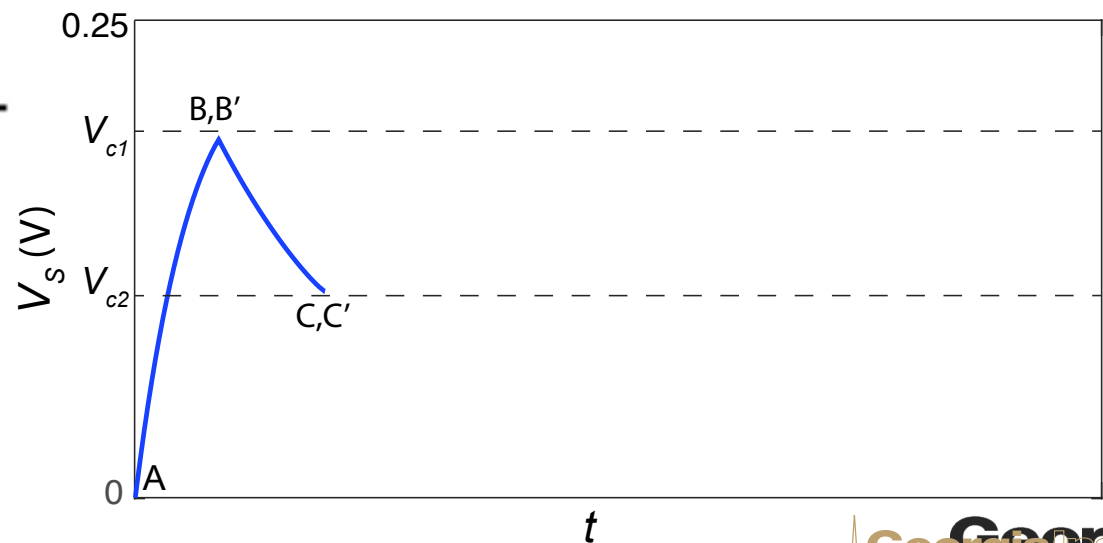
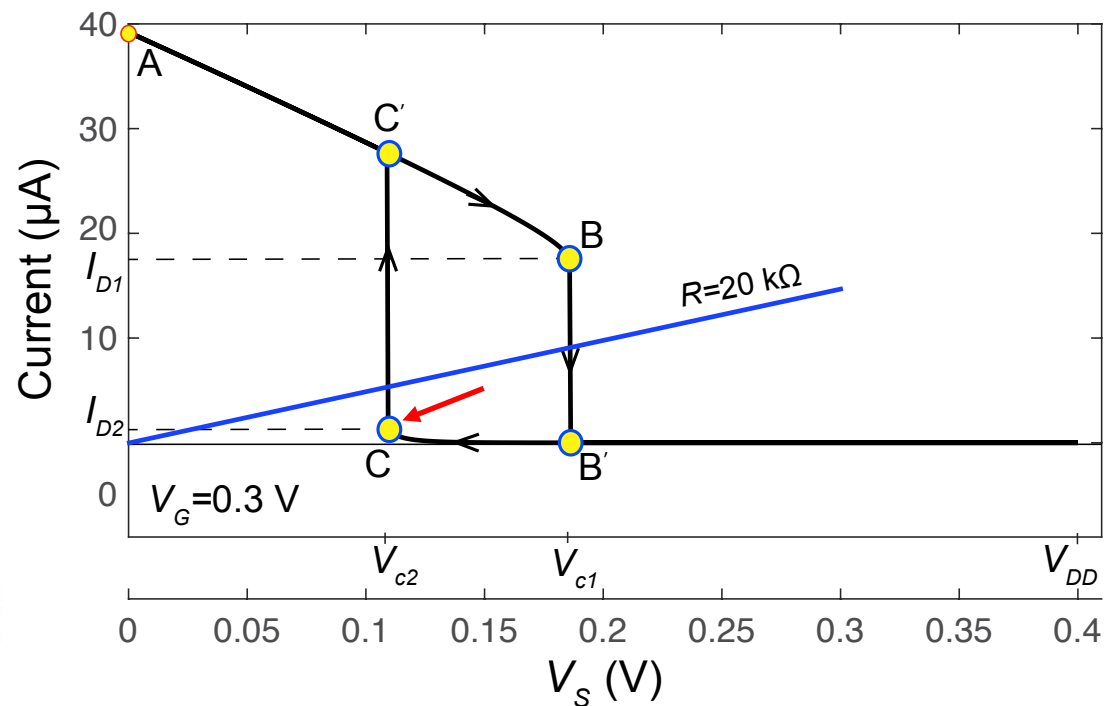
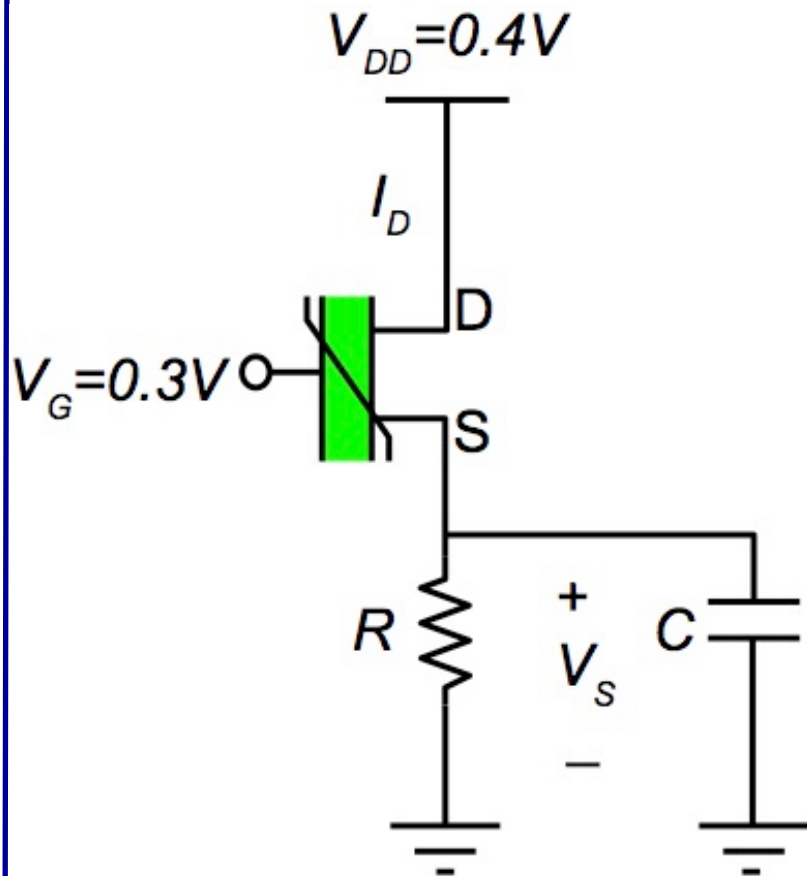
Dynamics of Ferroelectric Oscillator



No stable states in the abrupt transition region between B and

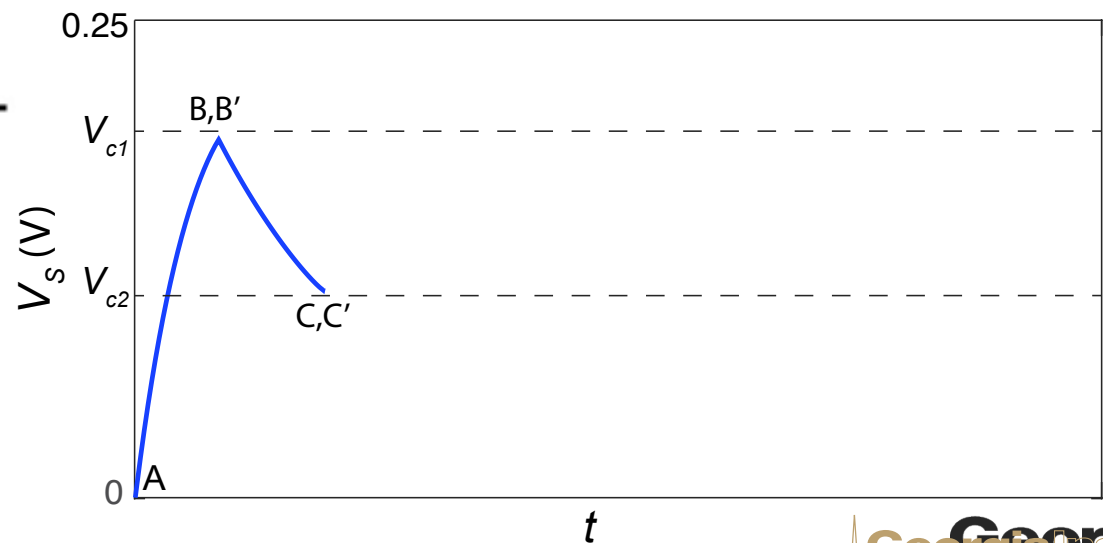
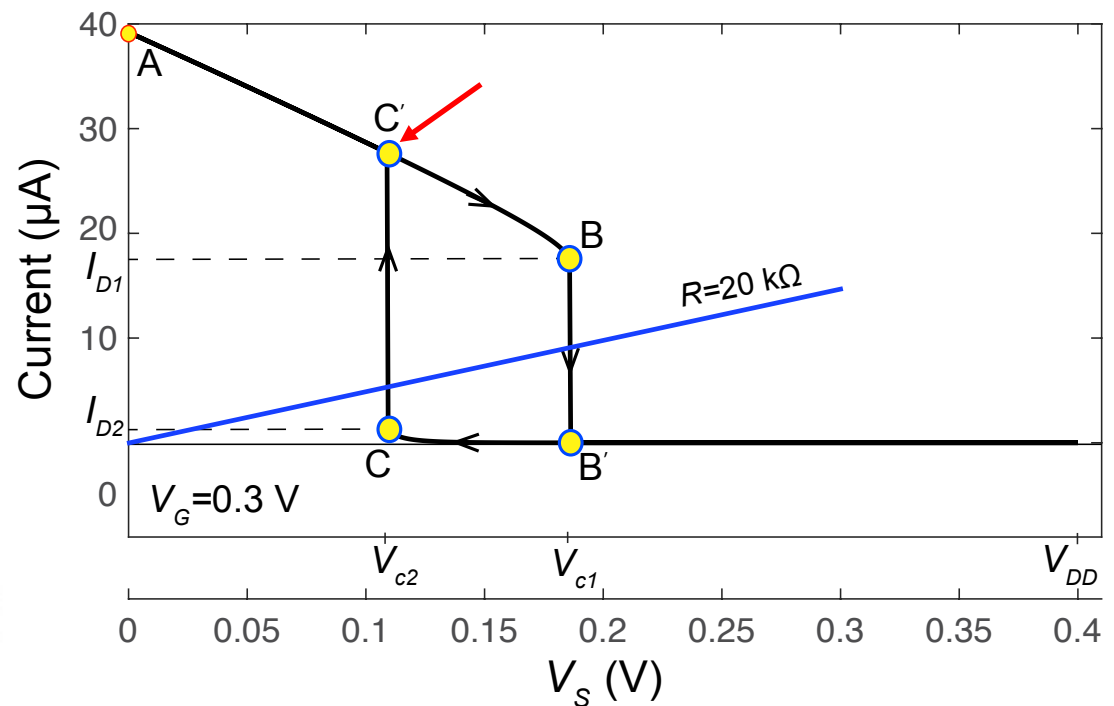
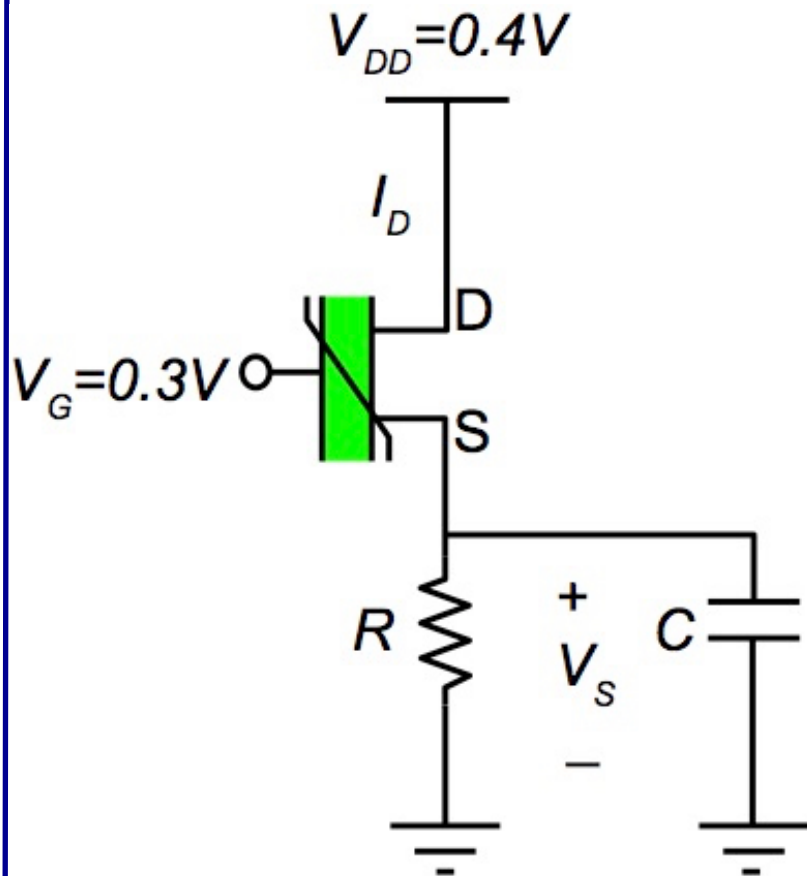
B'

Dynamics of Ferroelectric Oscillator



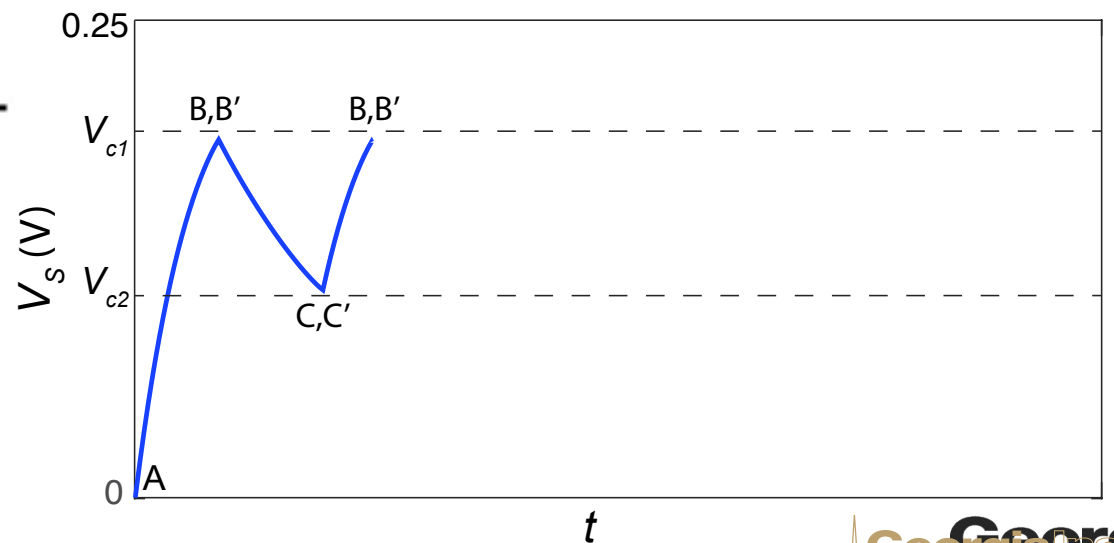
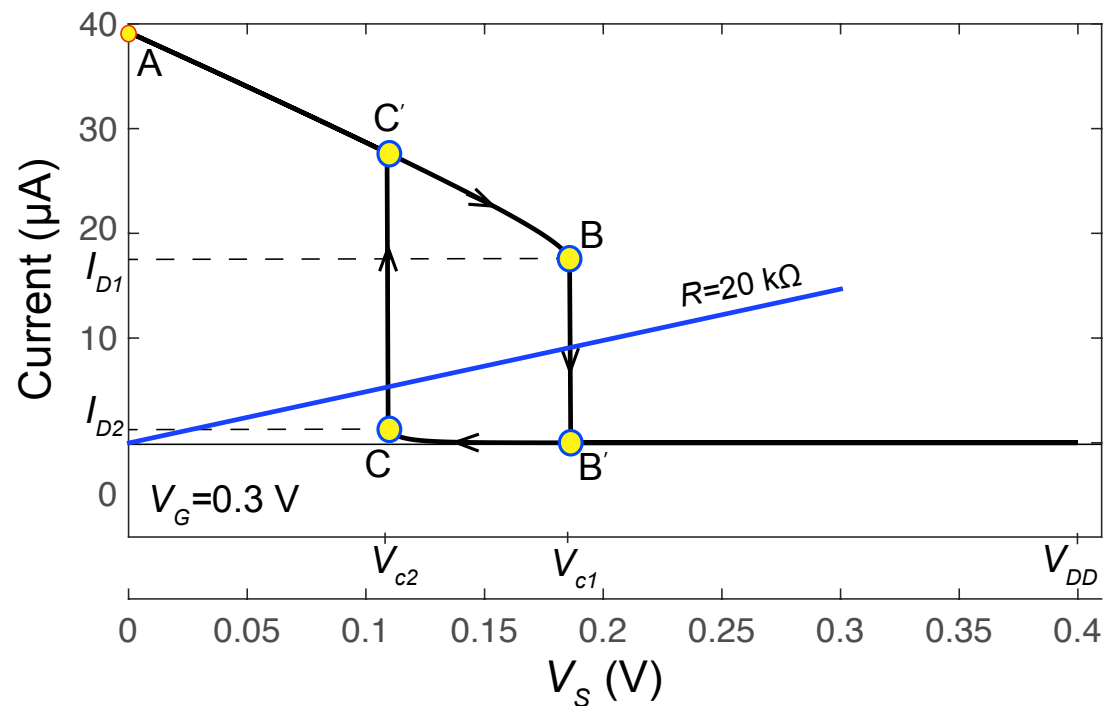
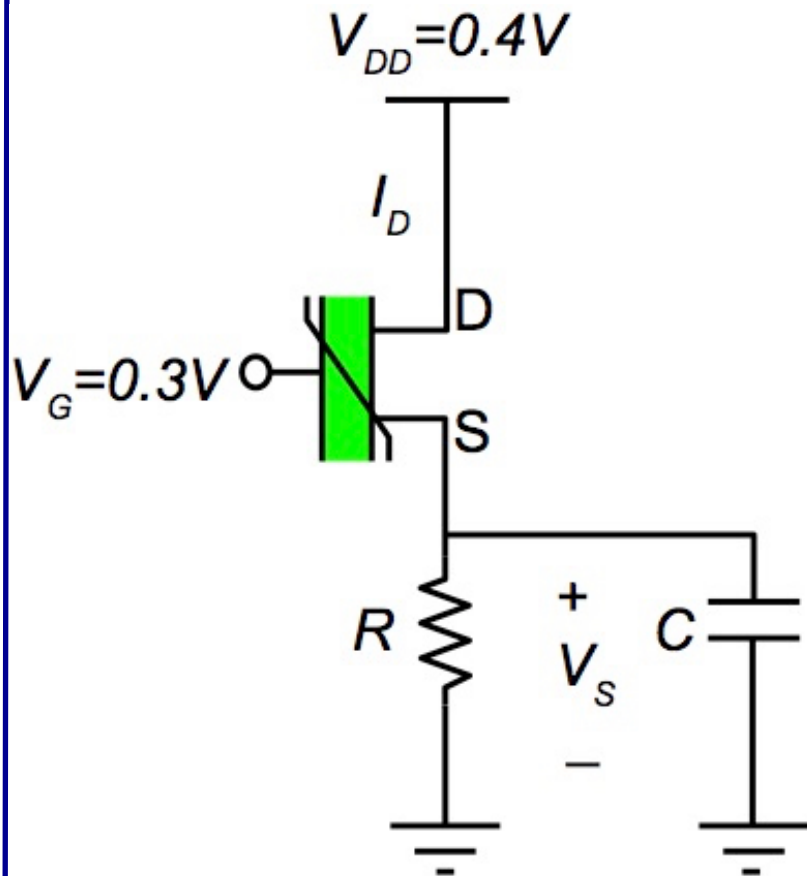
No stable states in the abrupt transition region between C and C'

Dynamics of Ferroelectric Oscillator



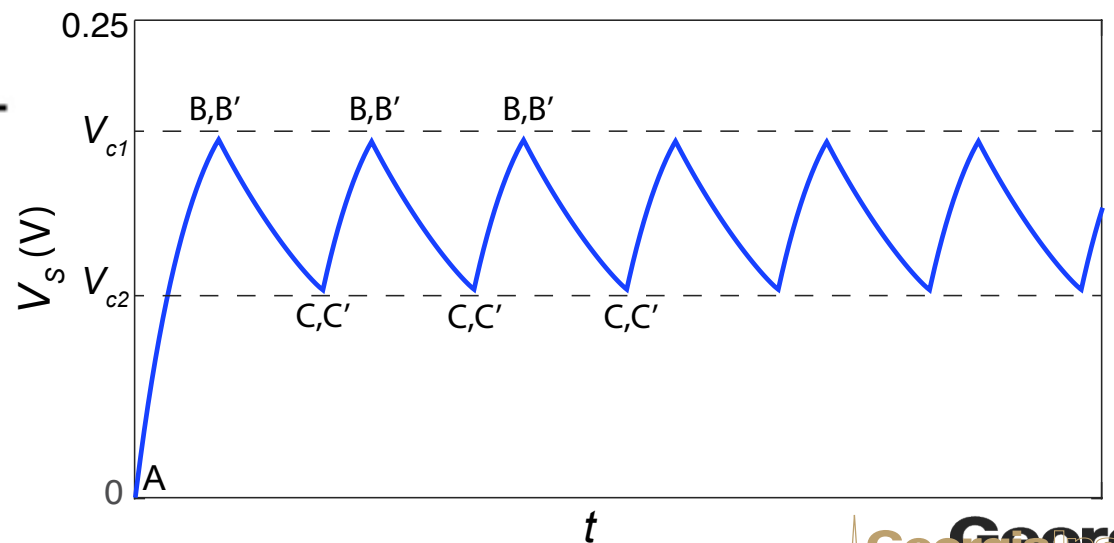
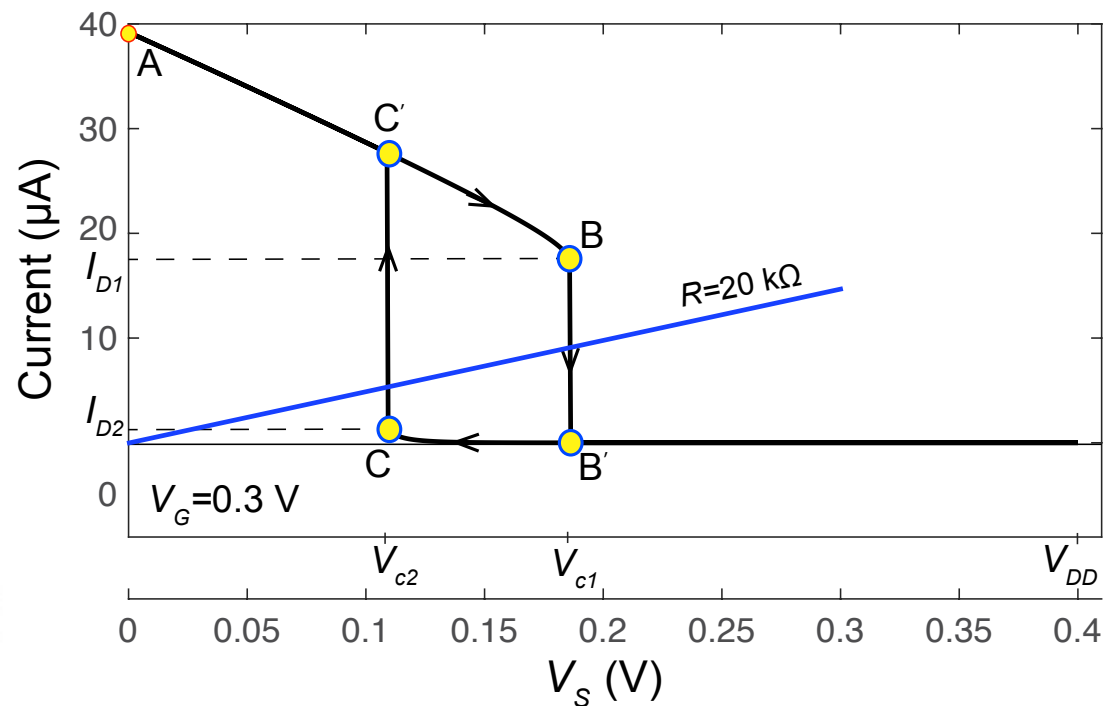
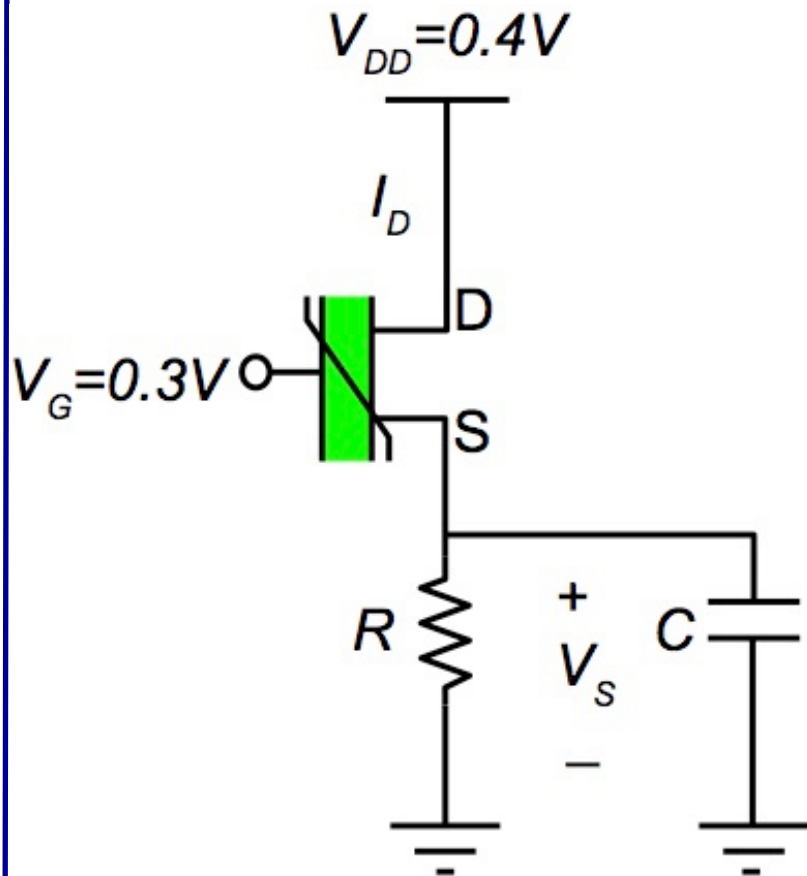
No stable states in the abrupt transition region between C and C'

Dynamics of Ferroelectric Oscillator



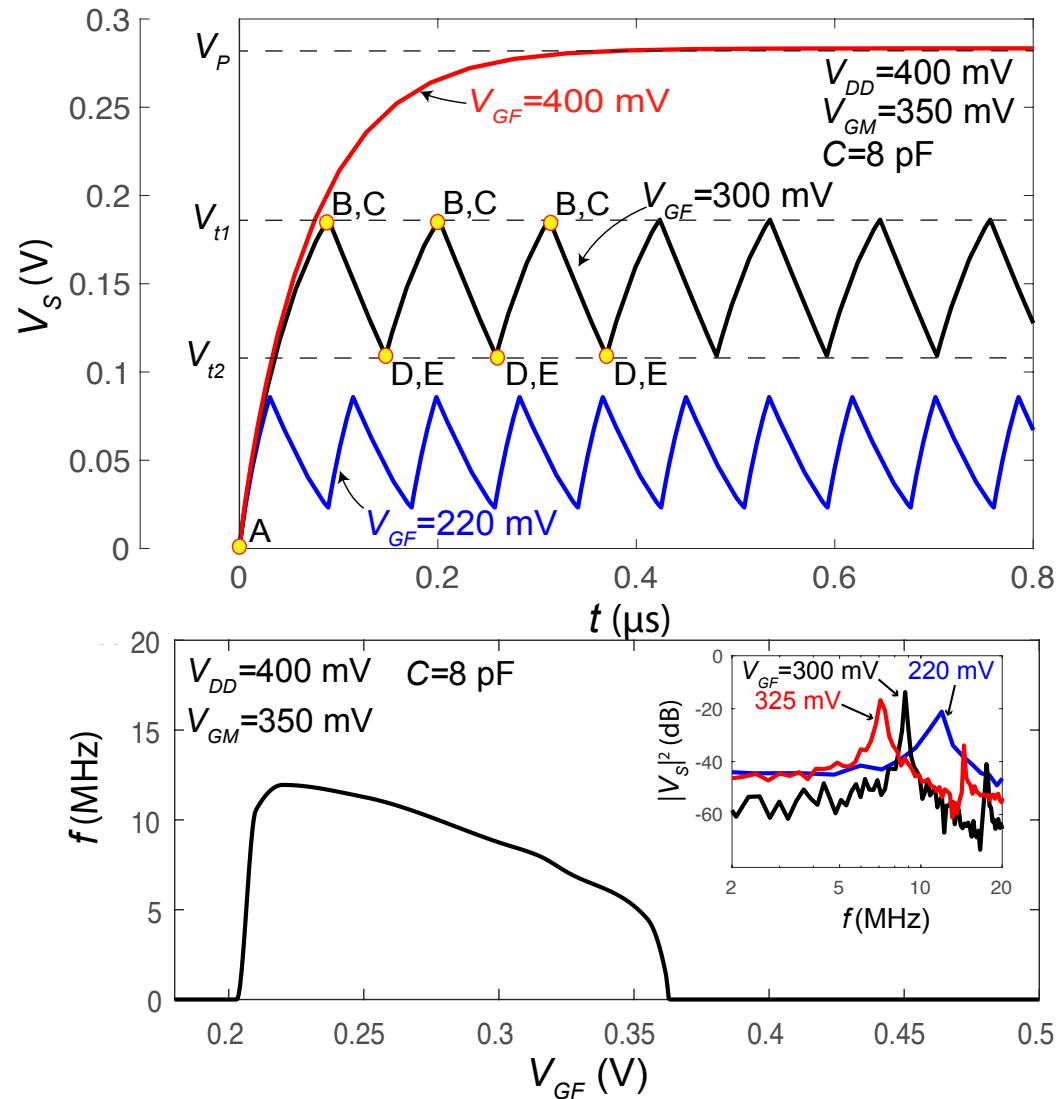
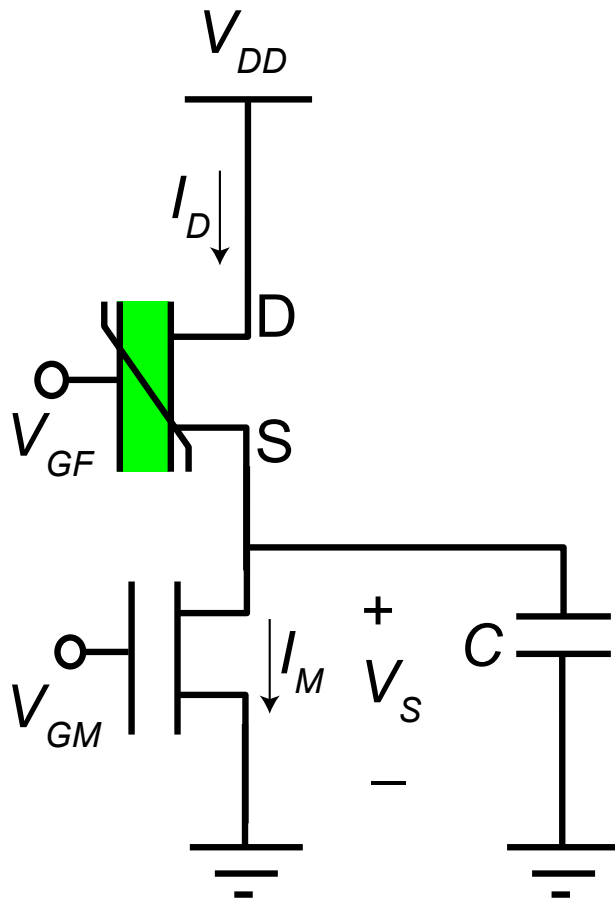
Proper design of FEFET hysteresis leads to sustained oscillation

Dynamics of Ferroelectric Oscillator



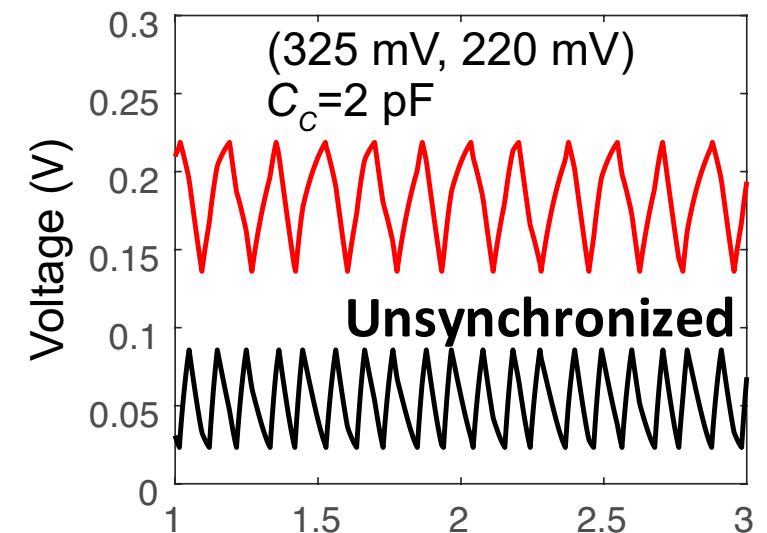
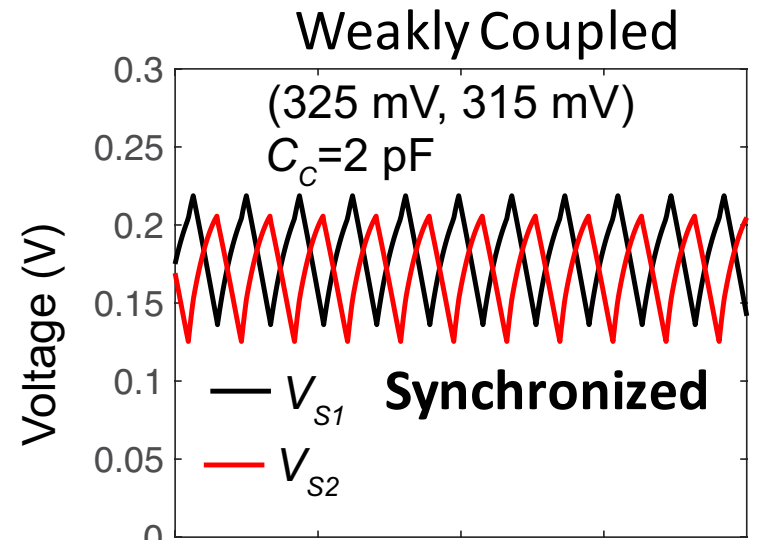
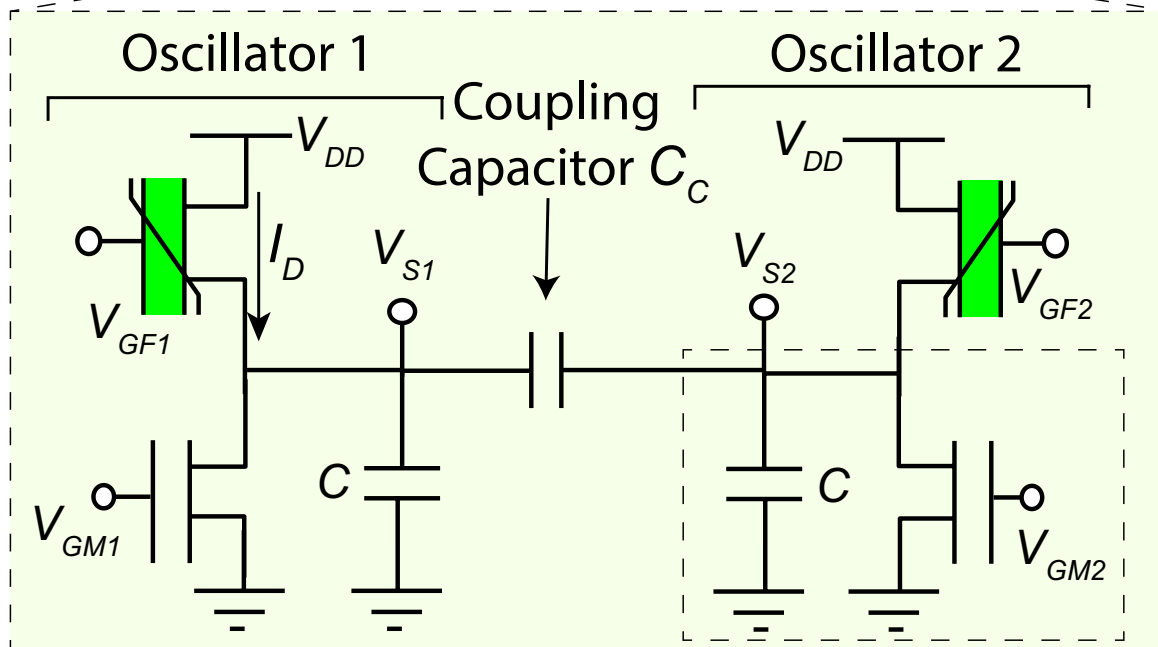
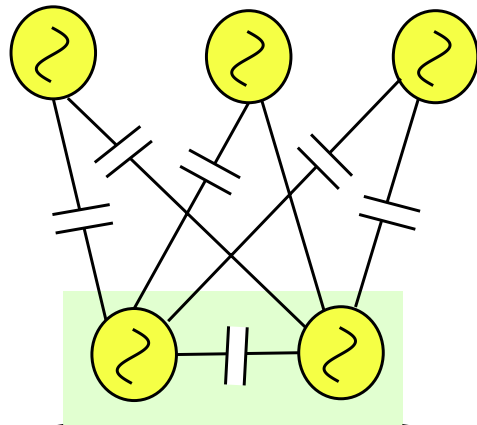
Oscillation repeats through the BB'CC' loop

Ferroelectric Oscillator



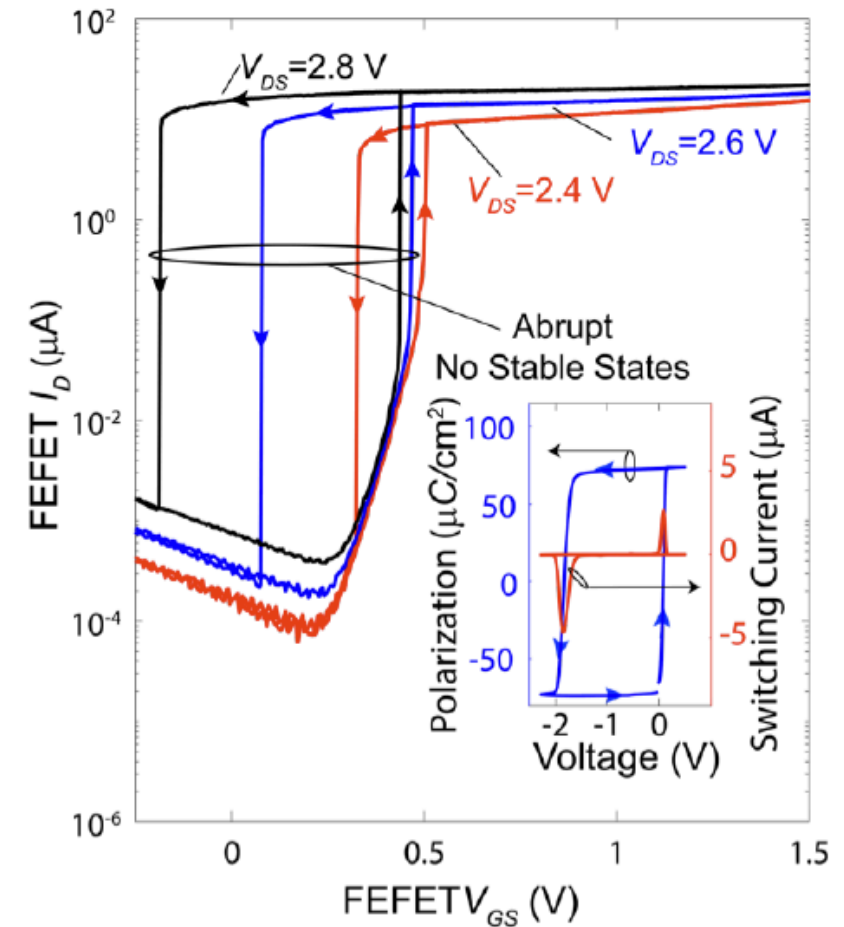
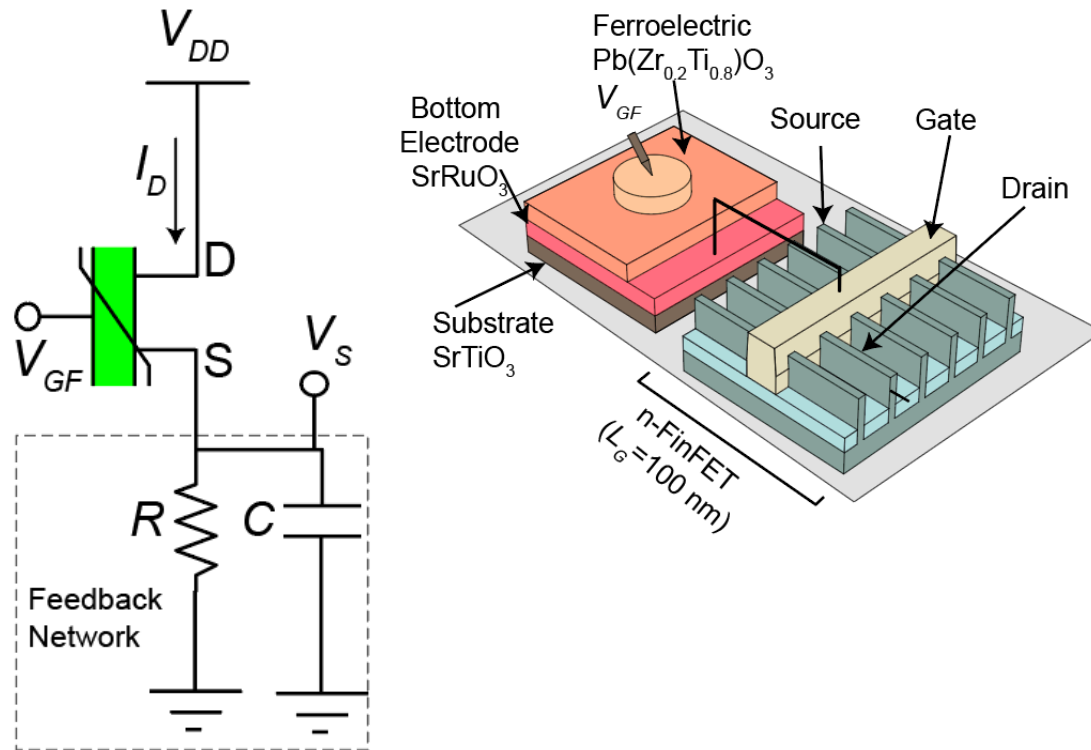
Gate voltages can be used to control oscillations!

Coupled Ferroelectric Oscillator



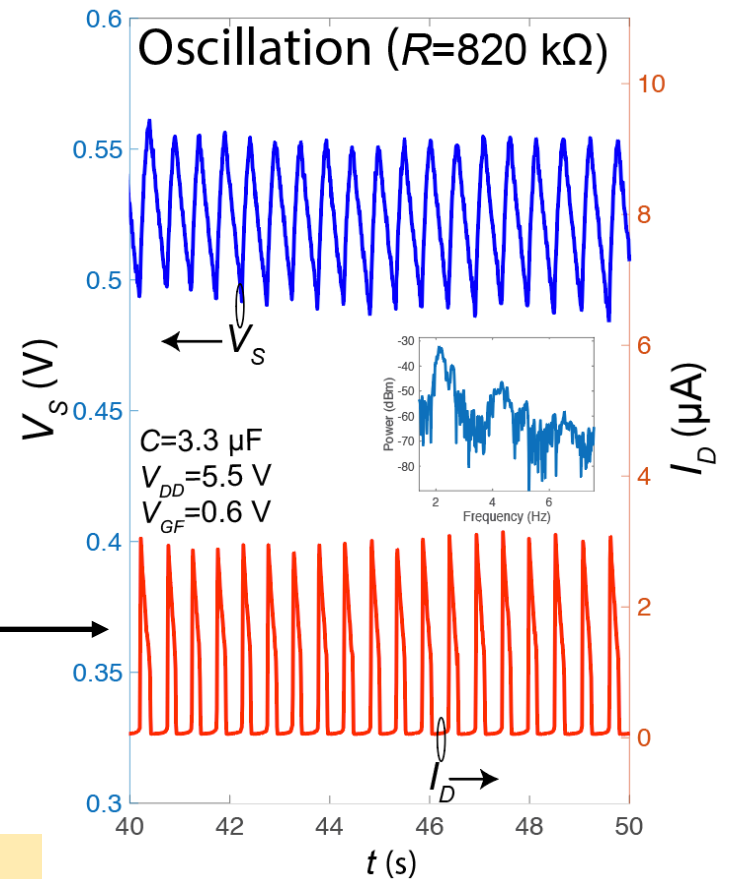
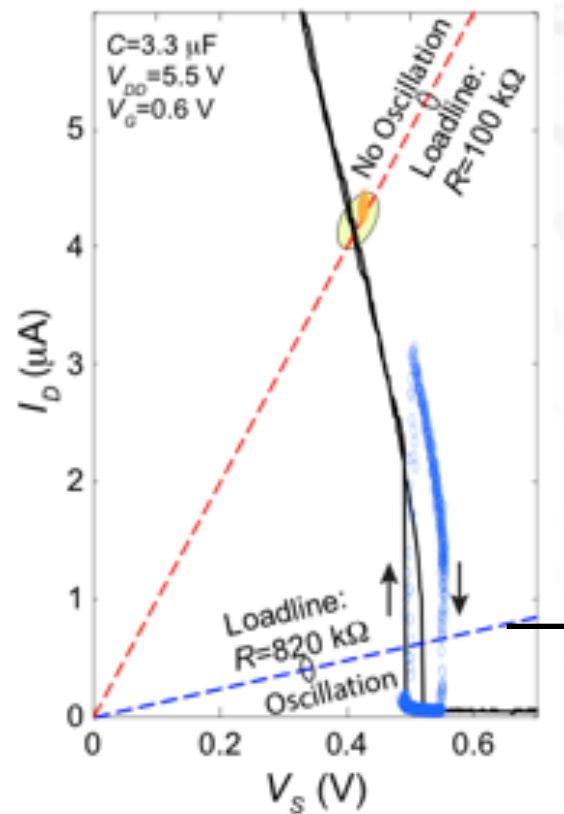
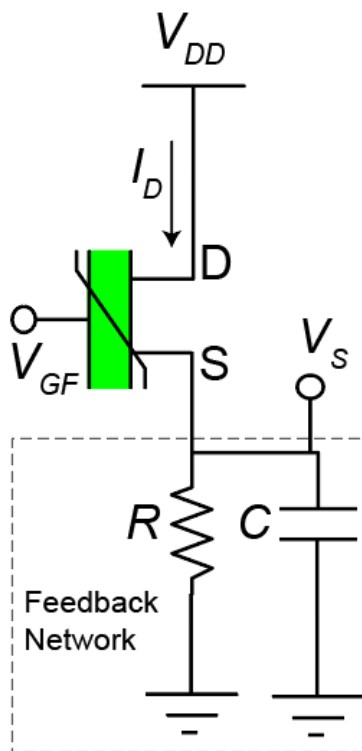
Synchronization dynamics can be utilized to solve hard problems.

Experimental Ferroelectric Oscillator



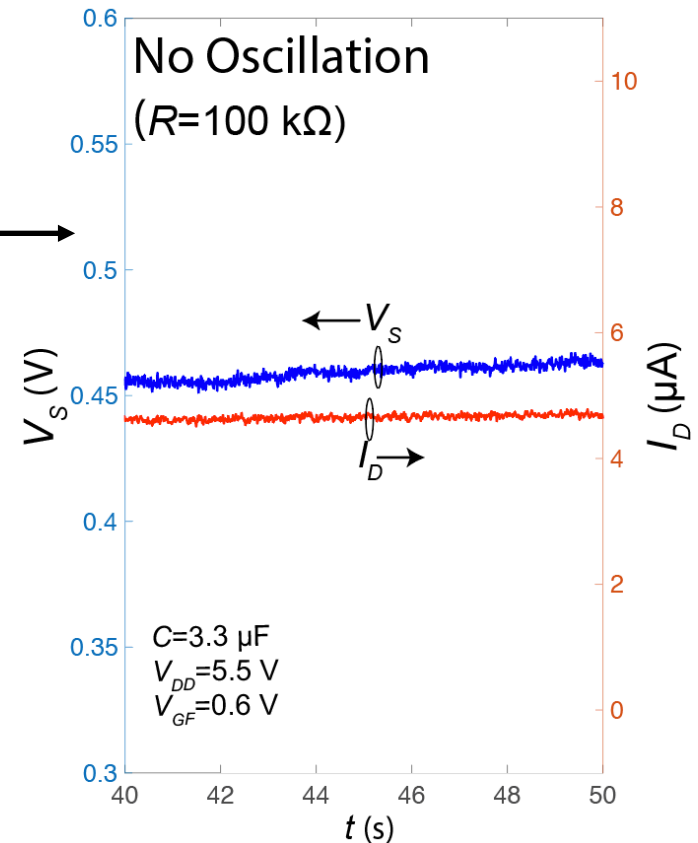
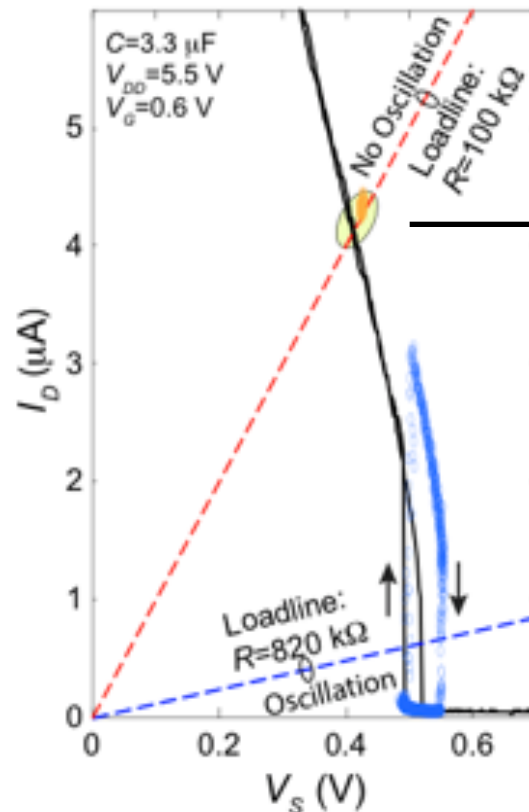
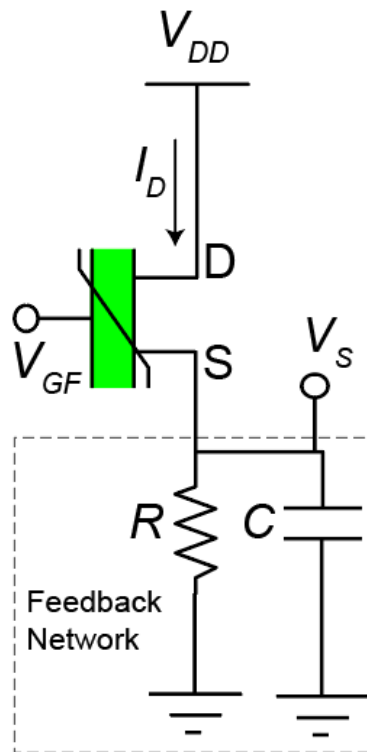
Abrupt transitions in externally connected FEFET are the key!

Experimental Ferroelectric Oscillator



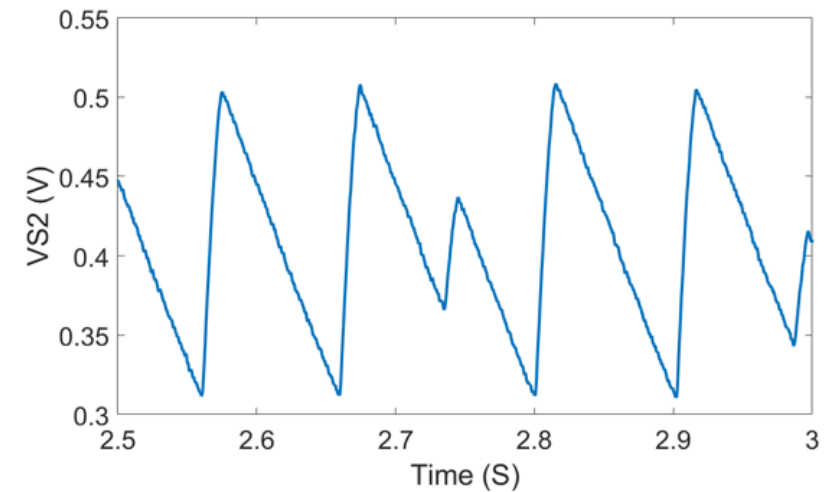
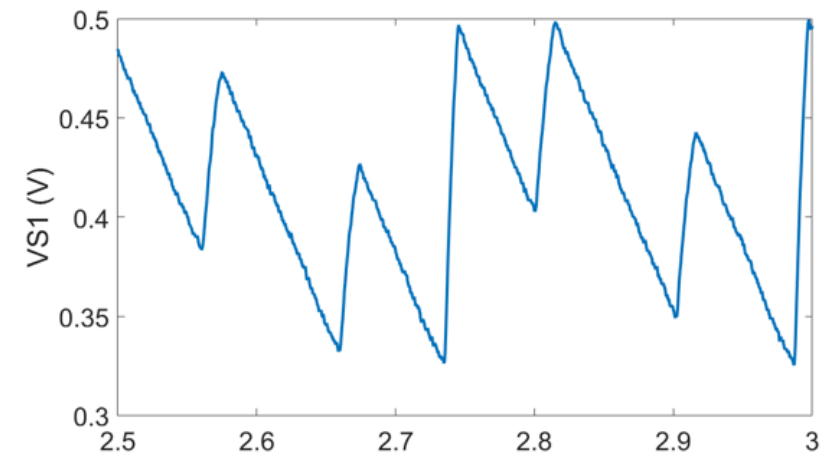
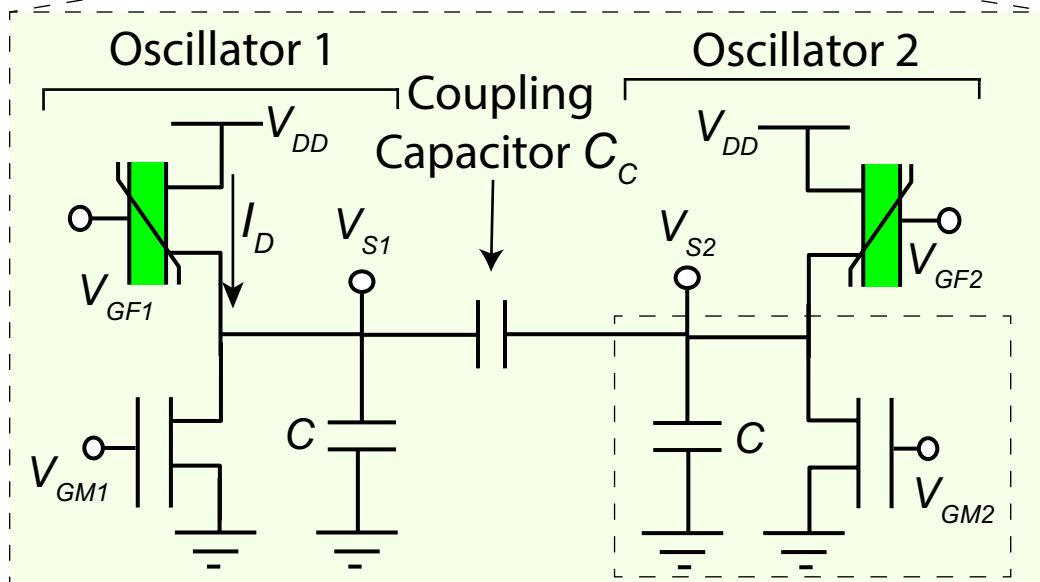
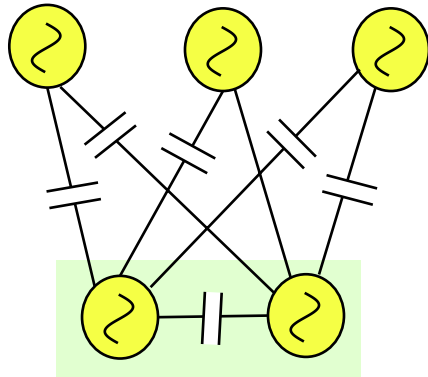
Oscillations are observed with $R=820 \text{ k}\Omega$.

Experimental Ferroelectric Oscillator

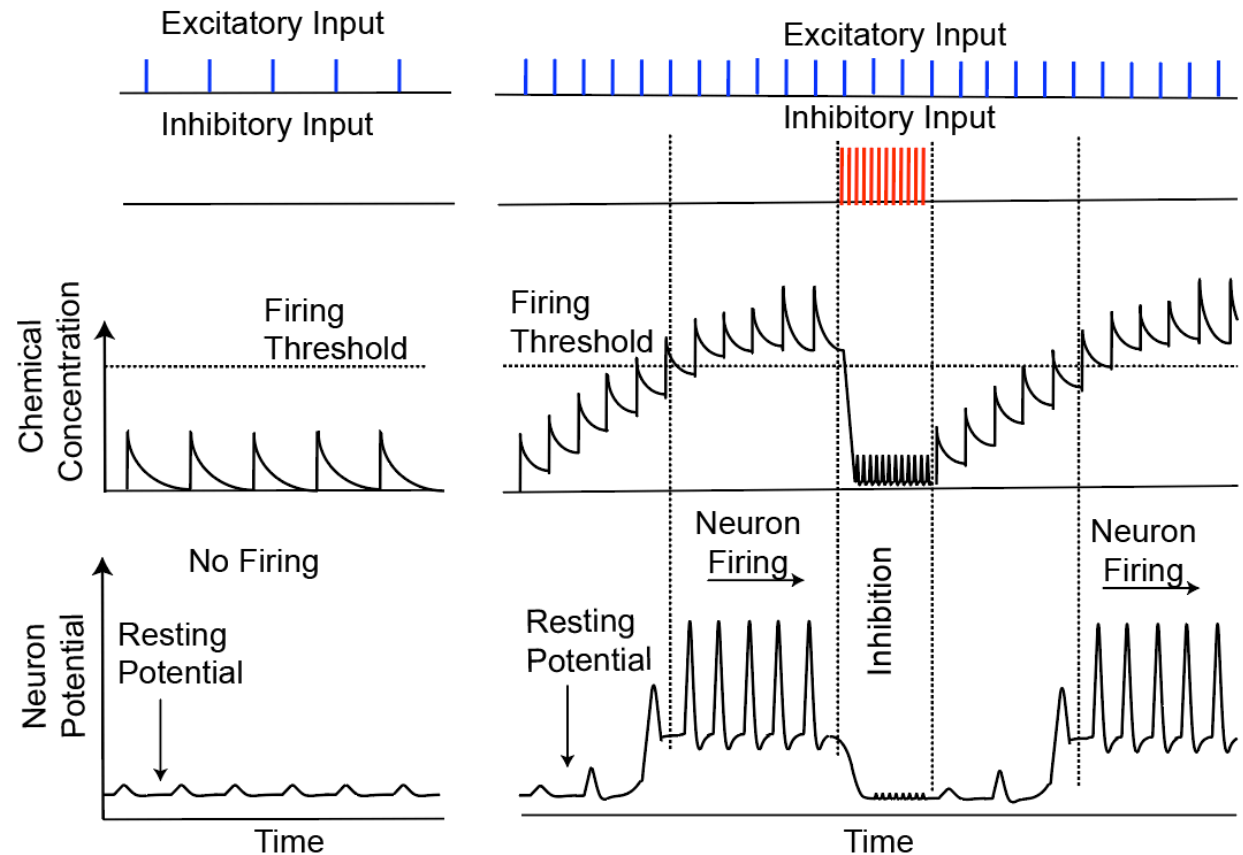
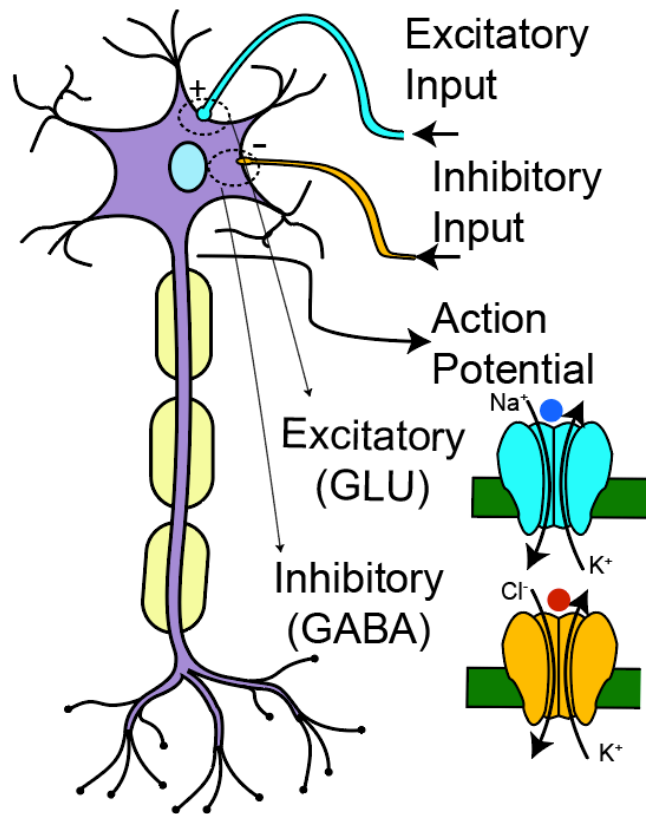


No oscillations are observed with $R=100 k\Omega$.

Experimental Coupled Ferroelectric Oscillator



Example 2: Spiking Neurons

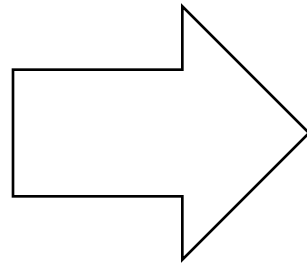
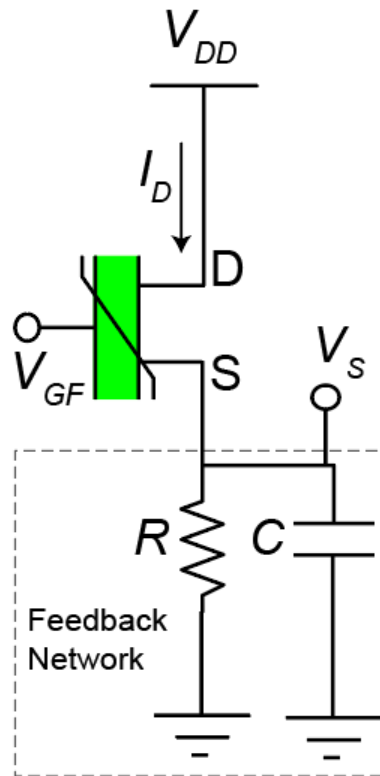


Biology: Inhibition required for regulation in activation of excitatory neurons; homeostasis.

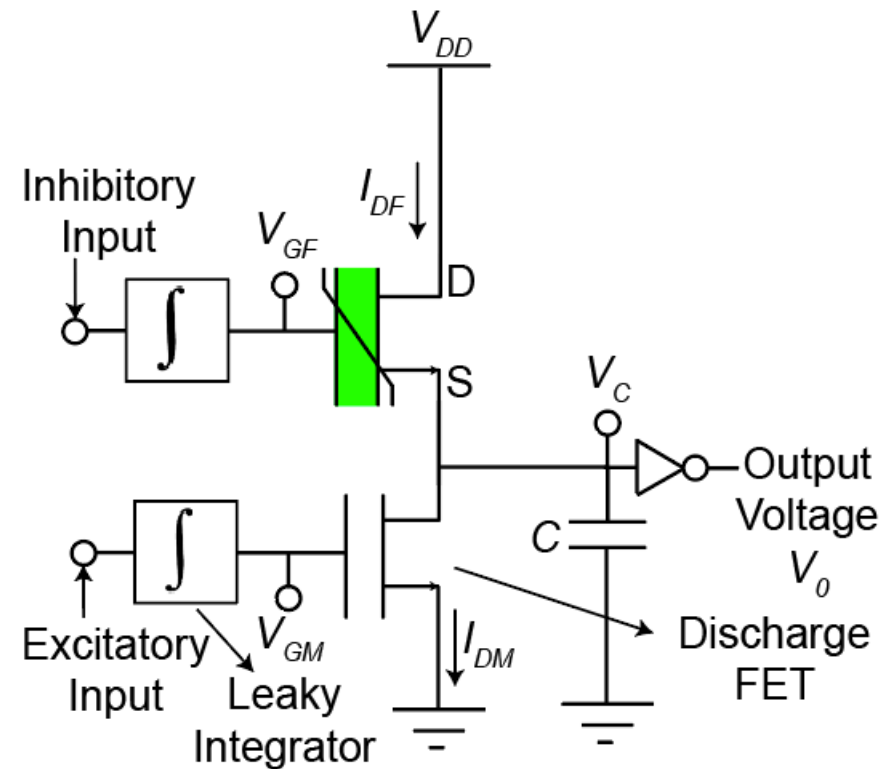
Bio-inspired computing: High accuracy in unsupervised learning.

Ferroelectric Spiking Neurons

Ferroelectric Oscillator

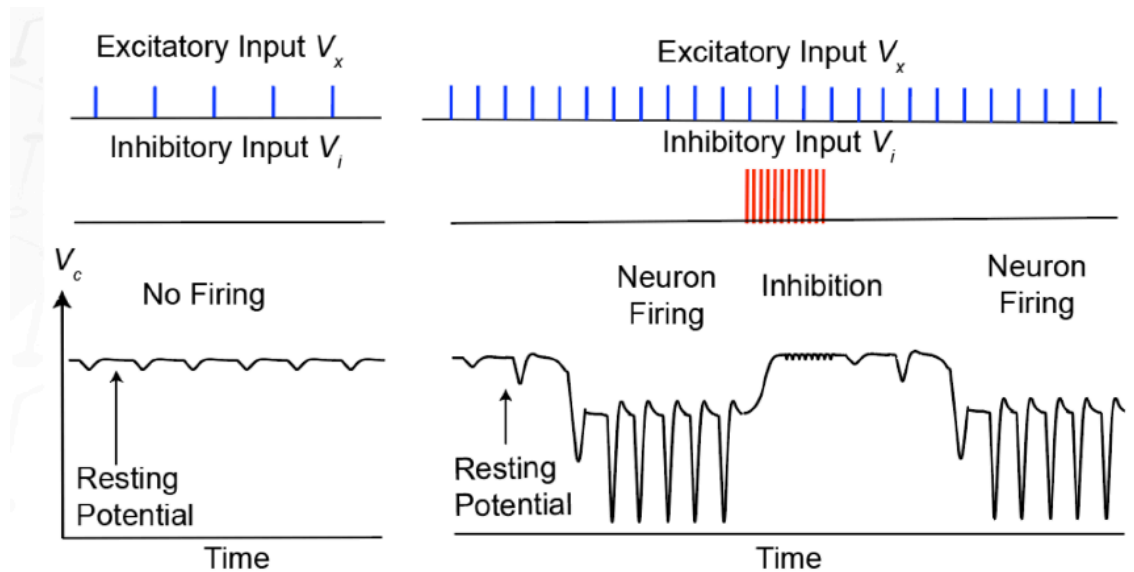
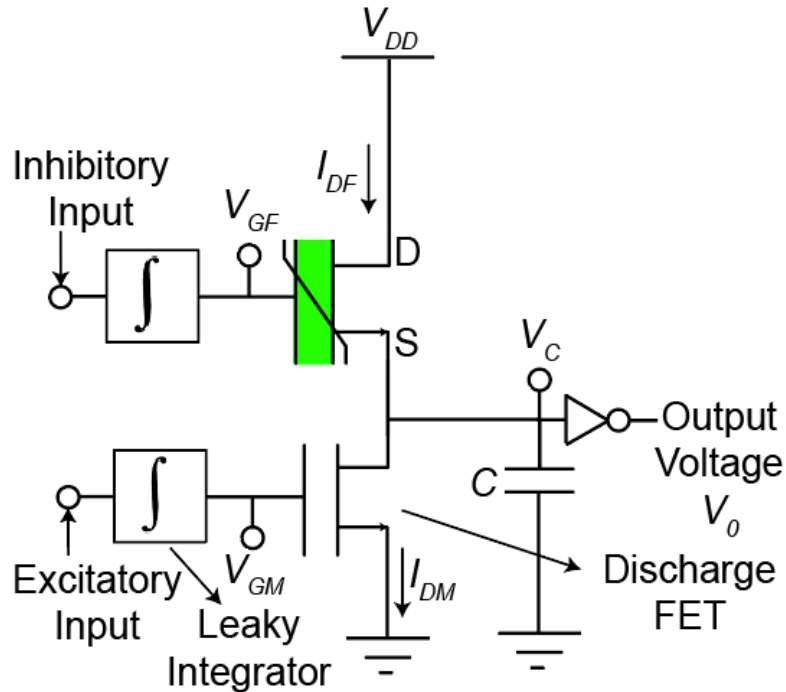


Ferroelectric Spiking Neuron



R replaced with a MOSFET; Leaky Integrator Added

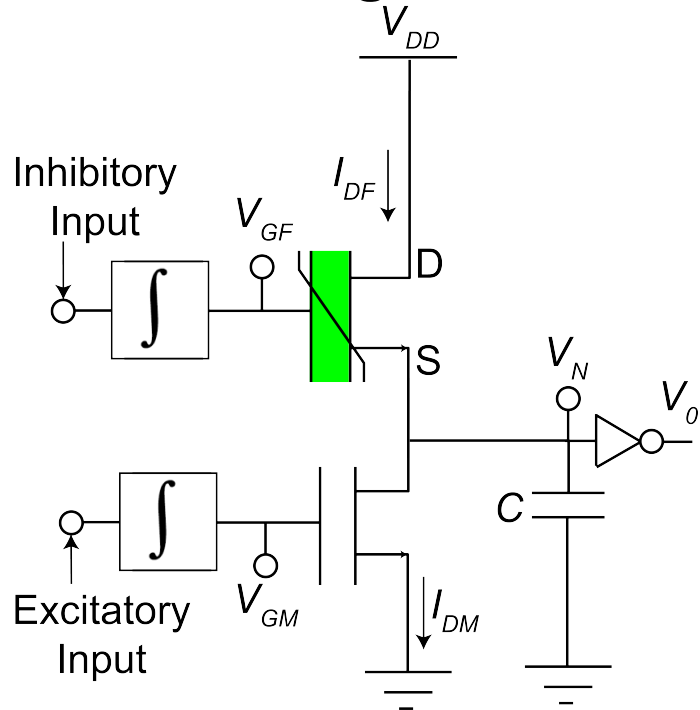
Ferroelectric Spiking Neurons



1FET-1T circuit primitive for neuron
with both excitatory and inhibitory inputs

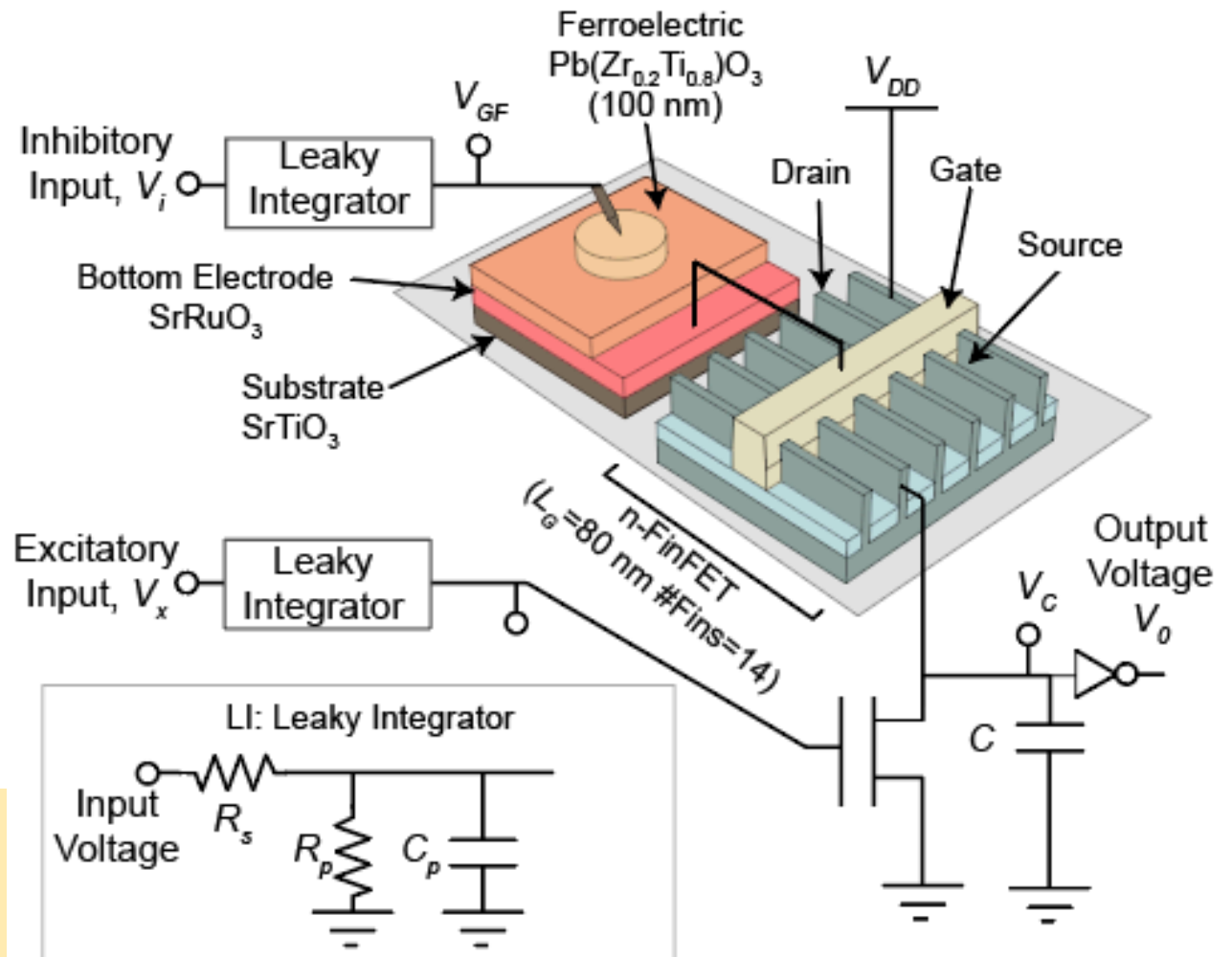
FE Spiking Neuron

Circuit Diagram

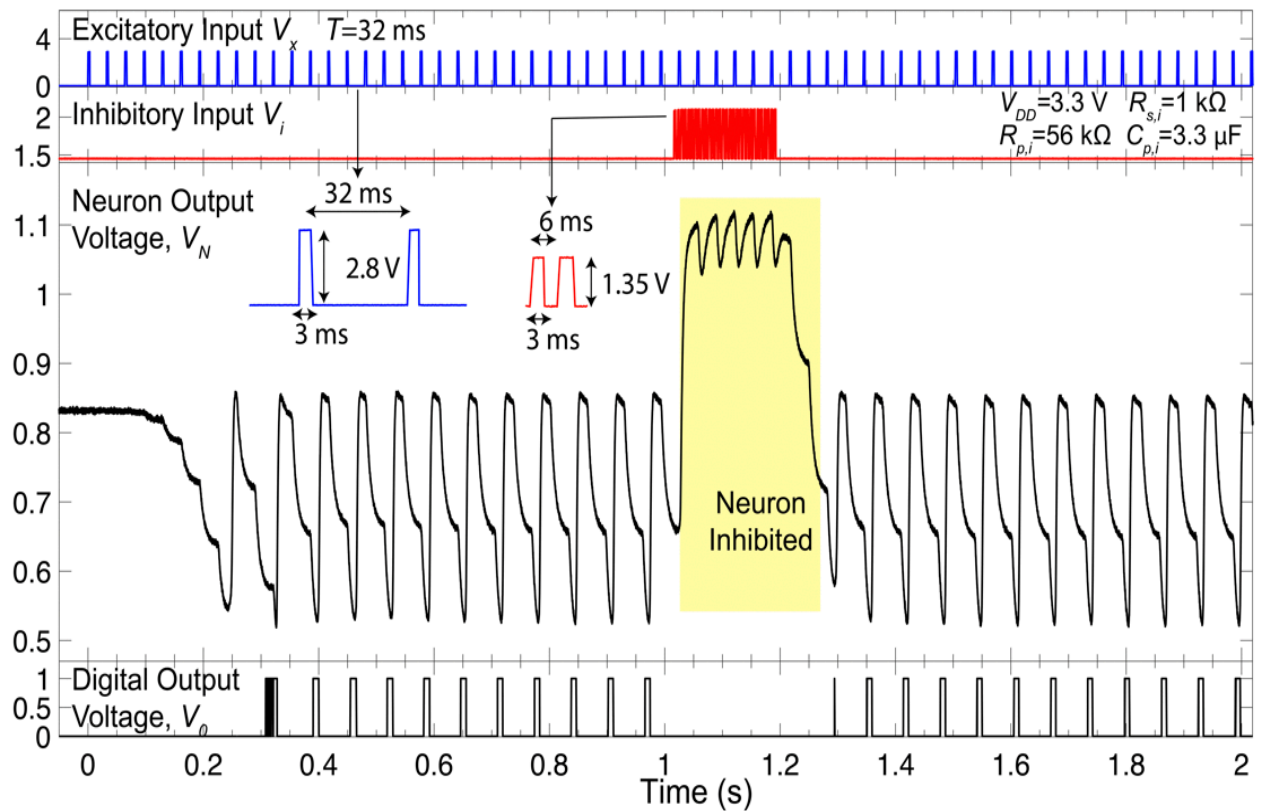
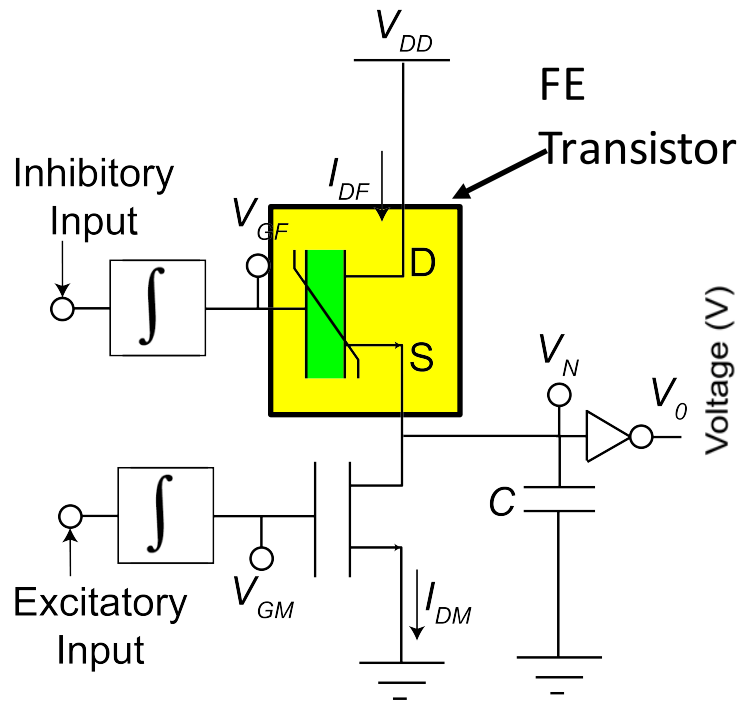


(It is amazing that such a cumbersome setup actually worked!)

Experimental Set-up



First demonstration of a ferroelectric neuron



Z. Wang et al. IEDM 2018

Z. Wang et al. EDL 2017

Fan et al. EDL 2019

research highlights

NEUROMORPHIC DEVICES

Ferroelectric spiking neurons

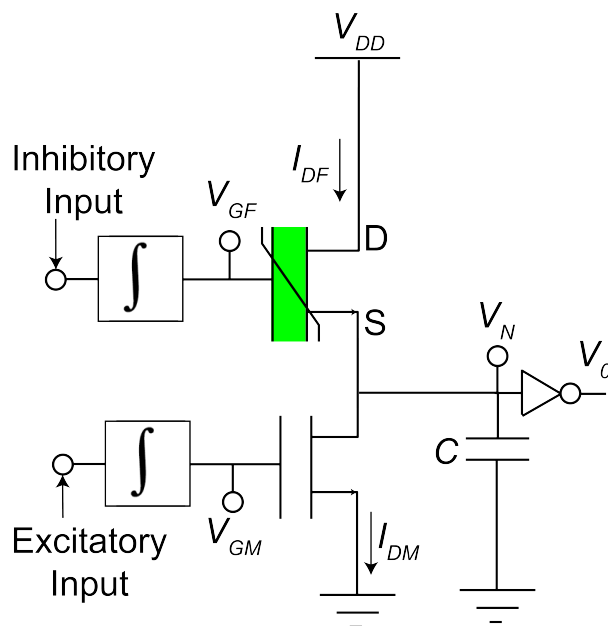
2018 IEEE Int. Electron Devices Meet. (in the press)

Brain-like computation using artificial neural networks (ANNs) could provide improved energy efficiency when compared

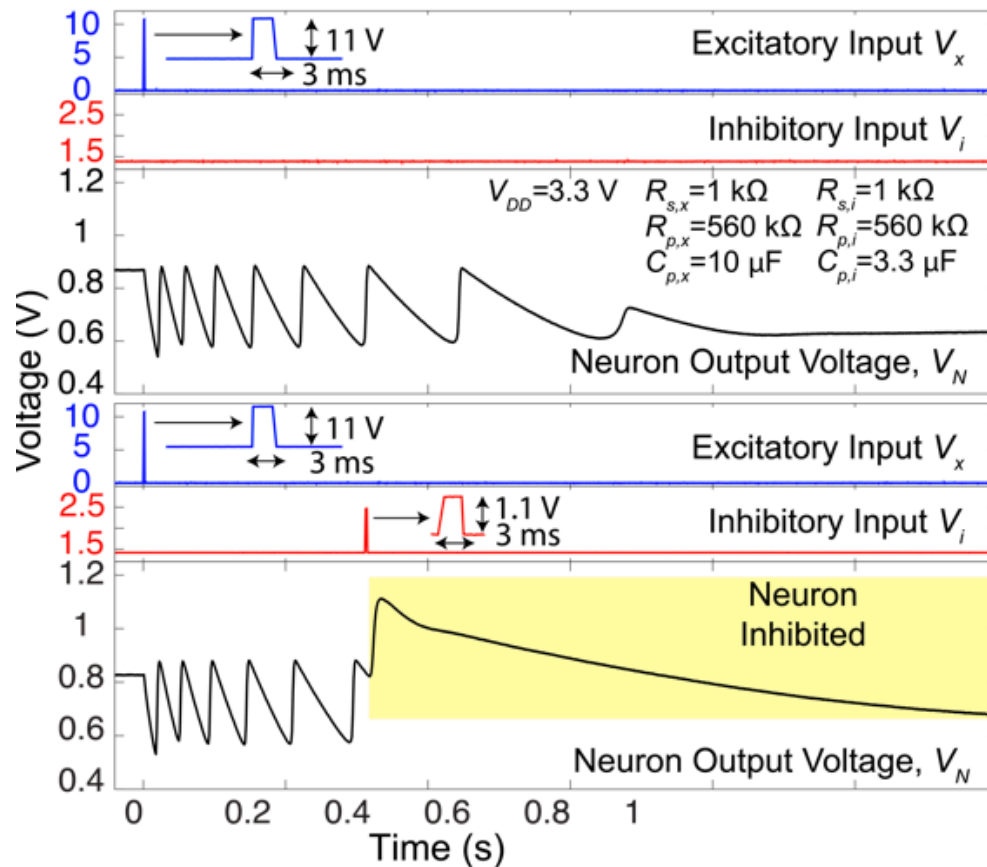
nature
electronics
(2019)

The first demonstration of an artificial neuron with integrated **inhibitory and excitatory** input!

Burst Mode and Inhibition



A large excitatory pulse generates a chirped spiking output, which can be inhibited by a large inhibitory pulse.



research highlights

NEUROMORPHIC DEVICES

Ferroelectric spiking neurons

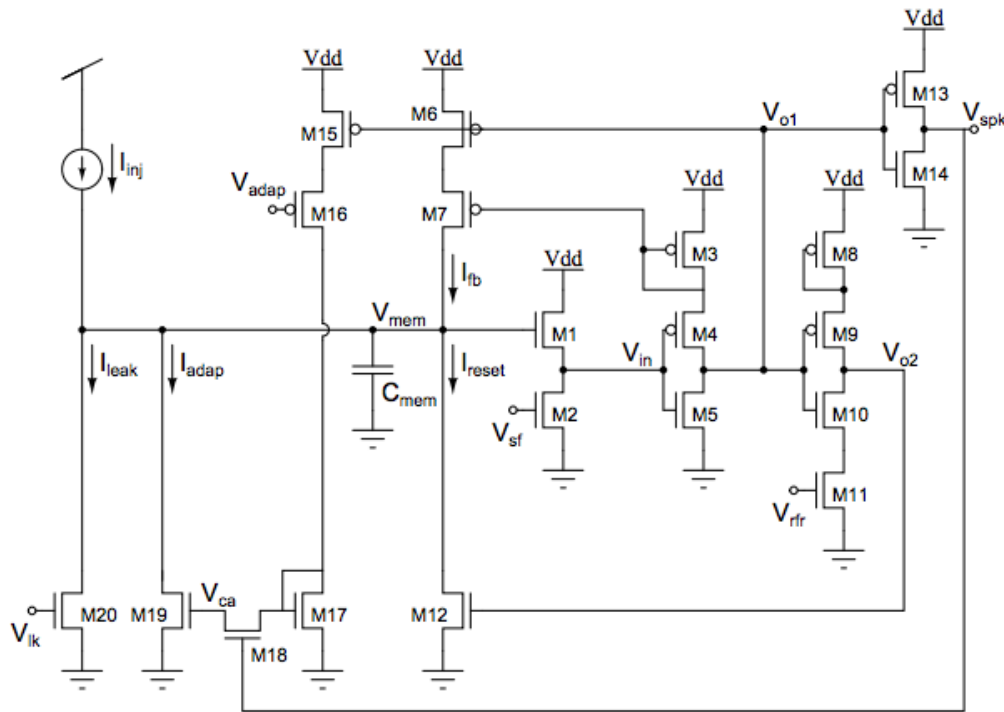
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electronics
(2019)

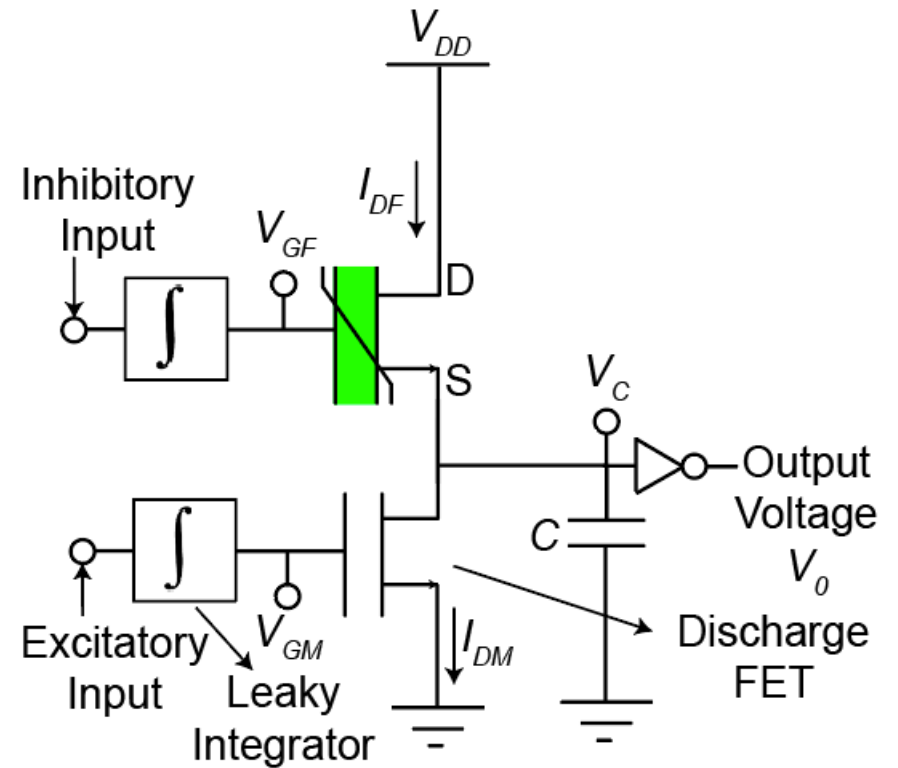
Why new devices?

CMOS Neuron

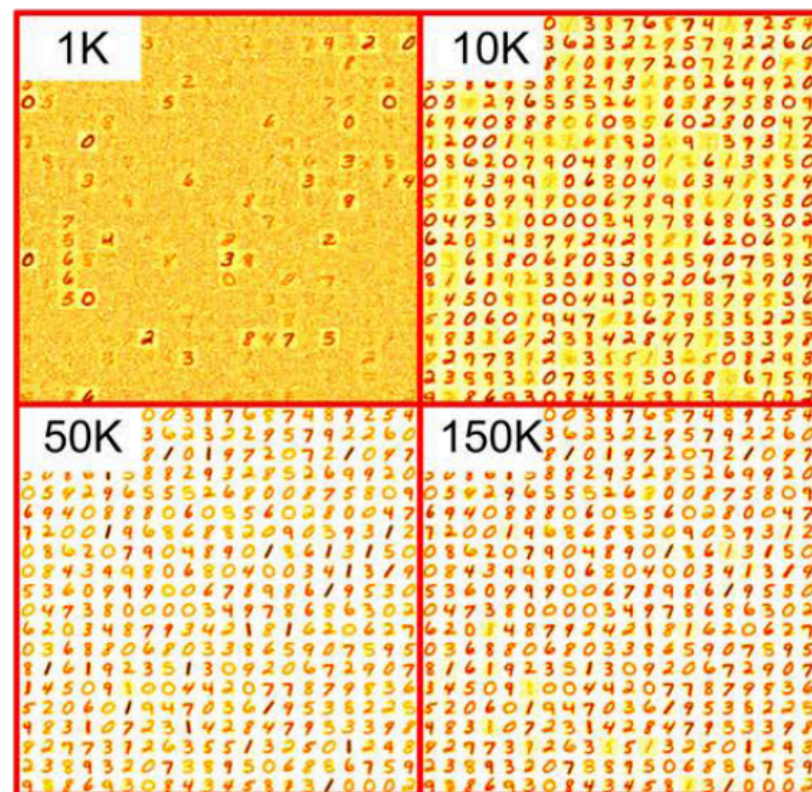
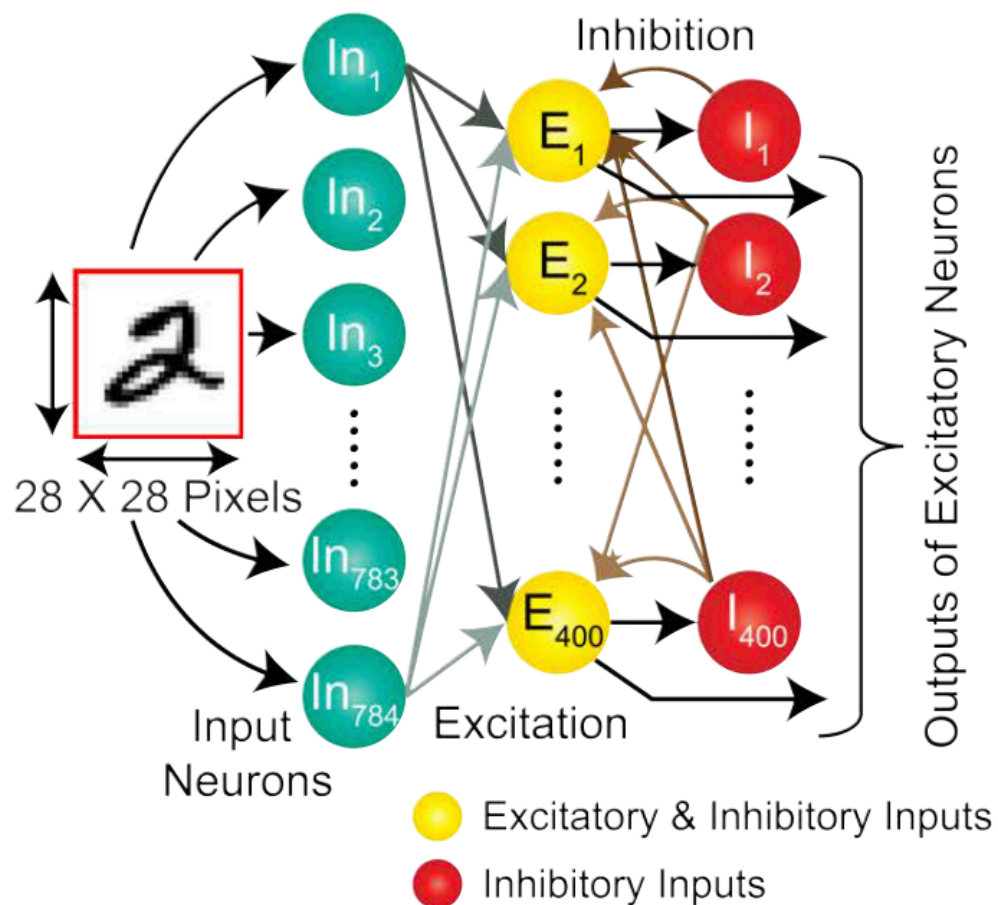


Indiveri et al. ISCAS 2003

Ferroelectric Neuron



Ferroelectric Spiking Neural Network Simulation



Unsupervised clustering of handwritten digits over training epochs

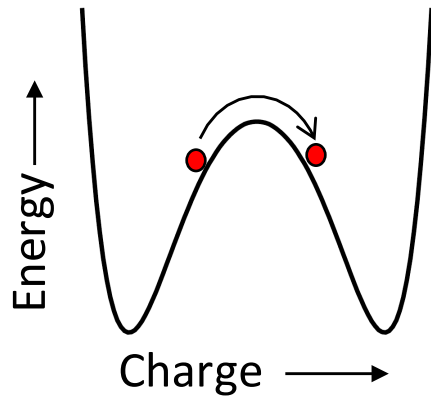
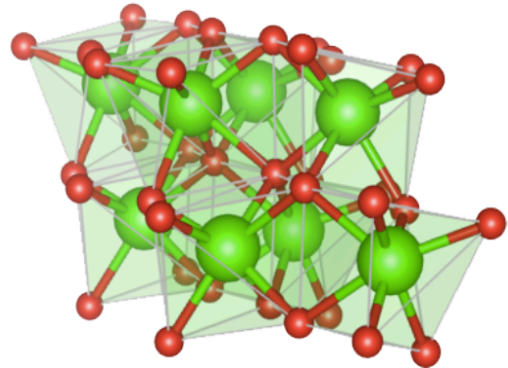
Classification accuracy of 93% on MNIST dataset at ~150,000 cycles

First demonstration of a ferroelectric neuron

	Indiveri ISCAS 2003	Amravati ISSCC 2018	Jerry et al. VLSI 2017	Current work
Technology	CMOS Analog, Mixed Signal		Emerging Technology	
Neuron Type	LIF	Multiply-Accumulate	LIF	LIF
Network Type	Spiking	Non-spiking	Spiking	Spiking
Data Encoding Architecture	Spike Timing	Multi-level perceptron	Spiking Rate	Spike Timing
Input Type	Excitatory	Excitatory	Excitatory	Excit. & Inhib.
Device Count	15 T	64 T	1T - 1 VO ₂	1T - 1 FEFET
Synapse Weight	Pos. & Neg.	Pos. & Neg.	Pos. & Neg.	Pos.
Training & Classification	Unsupervised	Reinforcement	Supervised	Unsupervised
Power	10 nW	125 nW	Not reported	3.6 nW

Ferroelectric Neuromorphic FET

Ferroelectric Oxide



Hysteresis
& Non-volatility

Gain

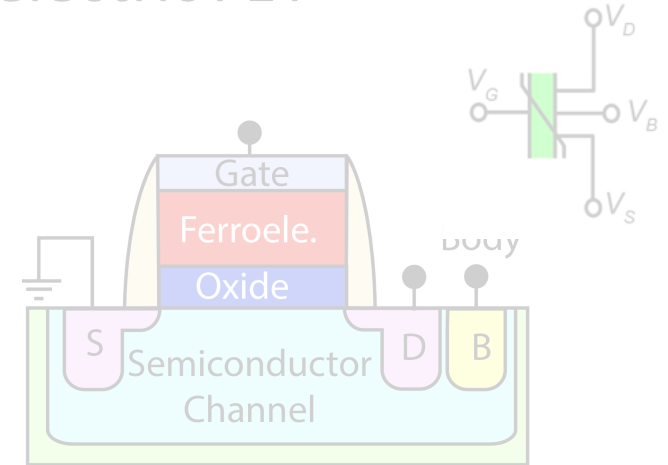
Plasticity

Polymorphism

Stochasticity

Circuit
Configurability

Ferroelectric FET



NN

PIM

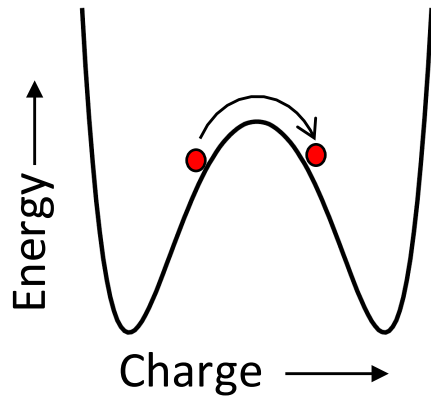
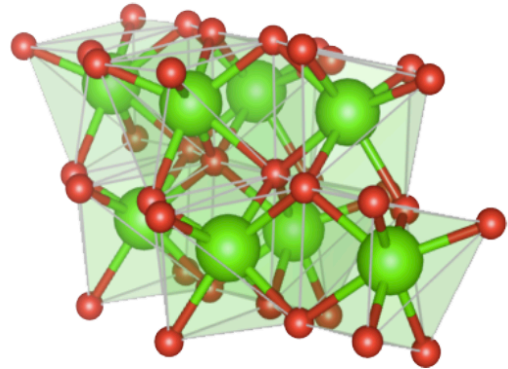
Osc



Ferroelectric materials have
wide range of interesting
dynamical properties!

Ferroelectric Neuromorphic FET

Ferroelectric Oxide



Hysteresis
& Non-volatility

Gain

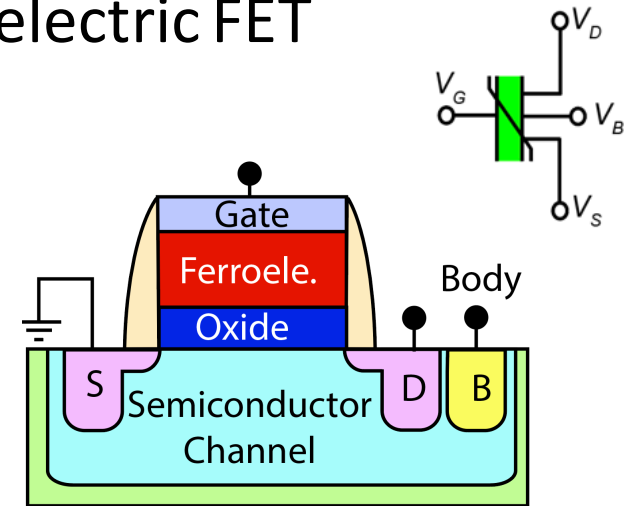
Plasticity

Polymorphism

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Circuit
Configurability

Ferroelectric FET



NN

PIM

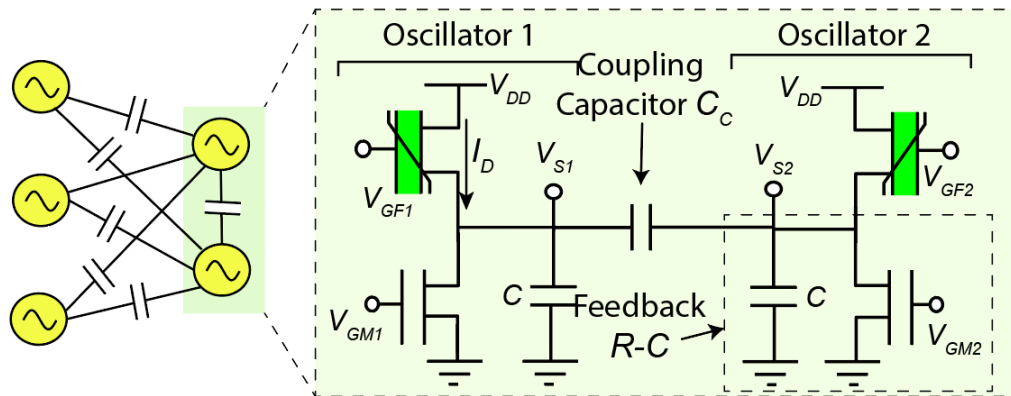
Osc

Neurons
& Synapses

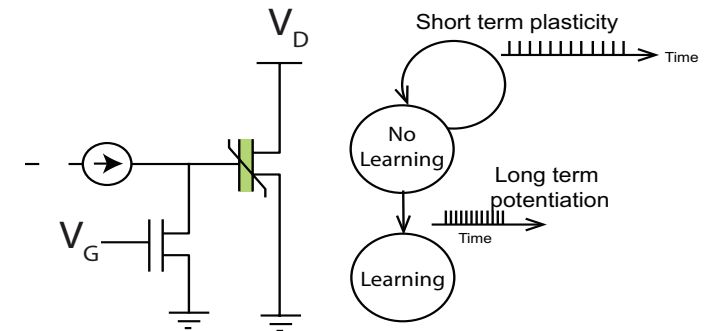
Ferroelectric FETs can enable different neuromorphic functions and non-von Neumann systems.

Family of Neuromorphic FEFET Circuits

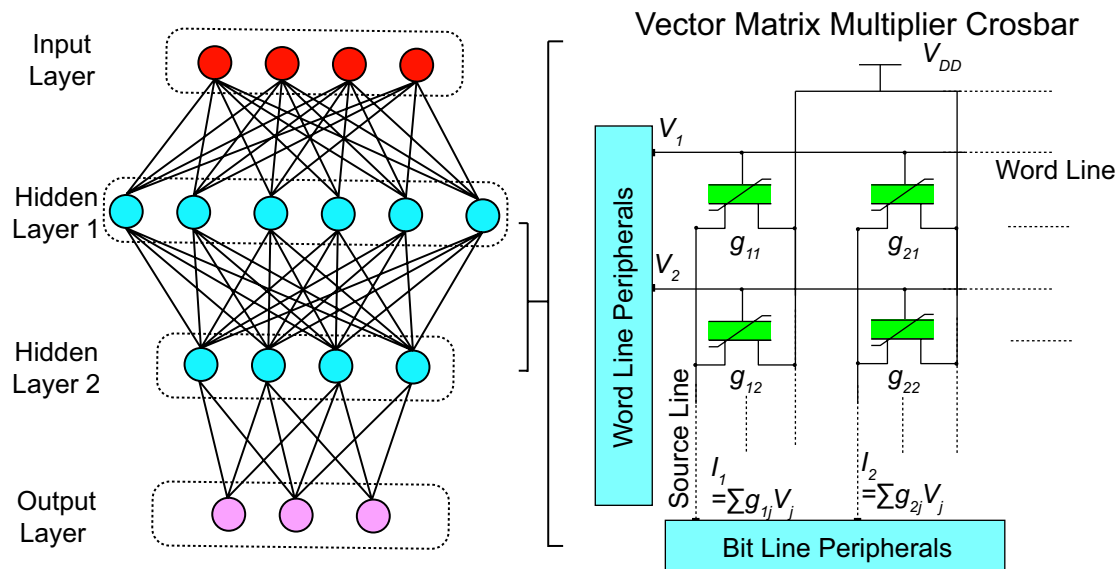
Coupled Oscillatory Systems and Neurons



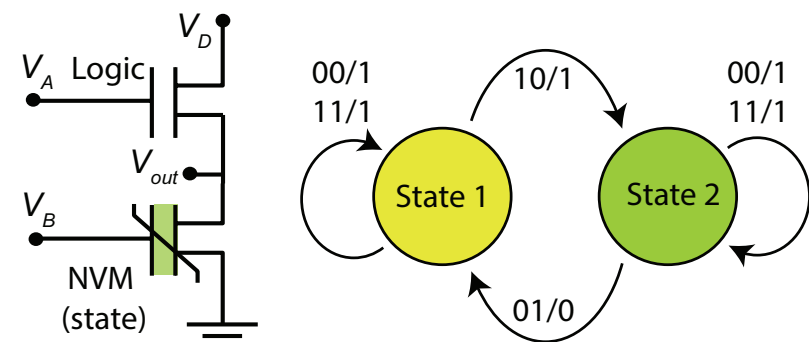
Synaptic Dynamics



Deep Neural Network

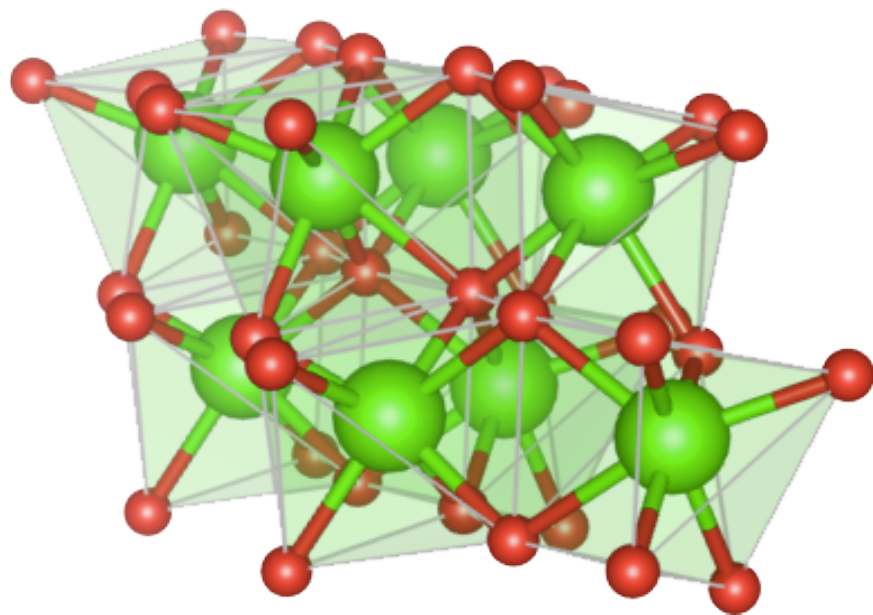


Nonvolatile Finite State Machines

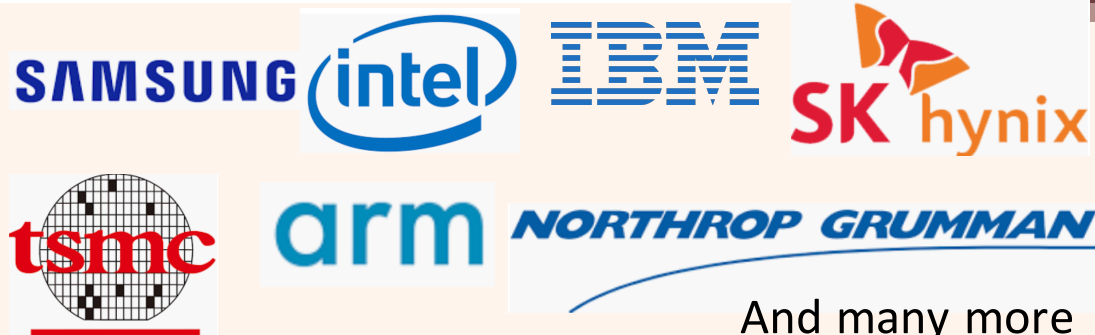


New CMOS Compatible Ferroelectrics

New class of ferroelectric materials have emerged which can be introduced in commercial fabs!



Commercial Fabs!



And many more

Semiconductor Industry and Computing

Article
January 2019

Artificial-intelligence hardware: New opportunities for semiconductor companies

By [Gaurav Batra](#), [Zach Jacobson](#), [Siddarth Madhav](#), [Andrea Queirolo](#), and [Nick Santhanam](#)

“AI could allow semiconductor companies to capture 40 to 50 percent of total value from the technology stack, representing the best opportunity they’ve had in decades.”

Historically the fraction has been 10-20% for the semiconductor industry!

<https://www.mckinsey.com/industries/semiconductors/our-insights/artificial-intelligence-hardware-new-opportunities-for-semiconductor-companies>.

Thank you



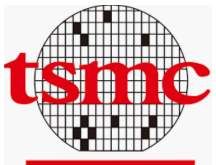
Semiconductor
Research
Corporation



SAMSUNG



IBM

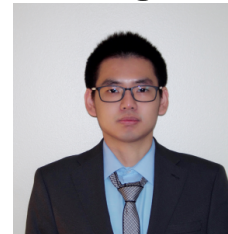


arm

NORTHROP GRUMMAN

And many more

Zheng W.



Sarah L.



Nujhat T.



Anthony G.

